Stellar Coronal Mass Ejections I. Estimating occurrence frequencies and mass-loss rates

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ABSTRACT

Stellar coronal mass ejections (CMEs) may play an important role in mass- and angular momentum loss of young Sun-like stars. If occurring frequently, they may also have a strong effect on planetary evolution by increasing atmospheric erosion. So far it has not been possible to infer the occurrence frequency of stellar CMEs from observations. Based on their close relation with flares on the Sun, we develop an empirical model combining solar flare–CME relationships with stellar flare rates to estimate the CME activity of young Sun-like and late-type main-sequence stars. By comparison of the obtained CME mass-loss rates with observations of total mass-loss rates, we find that our modeled rates may exceed those from observations by orders of magnitude for the most active stars. This reveals a possible limit to the extrapolation of such models to the youngest stars. We find that the most uncertain component in the model is the flare–CME association rate adopted from the Sun, which does not properly account for the likely stronger coronal confinement in active stars. Simple estimates of this effect reveal a possible suppression of CME rates by several orders of magnitude for young stars, indicating that this issue should be addressed in more detail in the future.

Key words: stars: activity – stars: mass-loss – stars: late-type

1 INTRODUCTION

Flares and Coronal Mass Ejections (CMEs) belong to the most energetic activity phenomena on the Sun. Whereas it is well established that other Sun-like and cooler stars generate flares (e.g. Gershberg 1975; Maehara et al. 2012; Balona 2015; Davenport 2016), the situation is different for stellar CMEs, since they are more difficult to observe. Obtaining a better understanding of CMEs on main-sequence FGKM stars is of special importance, because these stars could potentially host habitable planets. Since planetary habitability depends, among other factors, also on the conditions and stability of an atmosphere, all processes contributing to atmospheric erosion may severely restrict the habitability of a given planet, even if it orbits within the habitable zone of its host star. Young FGKM stars rotate faster than the Sun and have correspondingly higher levels of magnetic activity, leading to enhanced X-ray–UV (XUV) emission and frequent, powerful flares. Recent discoveries include superflares with bolometric energies up to 1037 erg (Maehara et al. 2012; Wu et al. 2015), some even occurring on slowly rotating Sun-like stars (Nogami et al. 2014). Enhanced radiation levels, either constant or temporarily variable during flares, affect planetary atmospheres by heating, ionization, and dissociation, leading to increased thermal escape (Watson et al. 1981; Erkaev et al. 2013; Lammer et al. 2014). In addition, strong stellar winds and frequent CME impacts may enhance non-thermal loss processes. Ion pick-up loss rates could be high in close orbits around young stars, which is especially relevant for planets in the habitable zones (HZs) of M dwarfs, since they have likely weak magnetic moments due to tidal locking (Lammer et al. 2007; Khodachenko et al. 2007a). Strong planetary magnetic fields could reduce the effect of this process and also moderate atmospheric losses due to thermal escape (Khodachenko et al. 2007b, 2015), but efficient polar winds could be generated if the atmospheres are highly ionized by the stellar XUV flux (Cohen & Gloejer 2012; Garcia-Sage et al. 2017; Airapetian et al. 2017). Simulations of the planetary system orbiting the M dwarf TRAPPIST-1 indicate that stellar and planetary magnetic field lines are connected and the stellar wind may flow directly onto the atmospheres of the planets, which could lead to strong atmospheric erosion (Garraffo et al. 2017).

On the Sun, CMEs are often associated with flares and are thought to be caused by the same underlying physical processes (Priest & Forbes 2002; Compagnino et al. 2017). However, not all flares are accompanied by CMEs and not all CMEs by flares. Flares without CMEs are typically shorter...
in duration and less energetic, whereas longer and more energetic flares are more likely to be associated with CMEs (Yashiro et al. 2006; Compagnino et al. 2017). Although there are also CMEs which are apparently not related to flares or other low coronal signatures (often termed “stealth CMEs”), these are typically less massive, less wide, and on average slower than normal CMEs (D’Huys et al. 2014). However, Alzate & Morgan (2017) recently found that all stealth CMEs studied by D’Huys et al. (2014) turned out to be artifacts of observational and data processing limitations. With new image processing techniques, low coronal signatures could be identified for all events, indicating that this type of CMEs likely does not comprise a physically distinct population.

CMEs are also often related to erupting prominences (EPs) which are believed to form the CME cores in the frequently encountered three-part structure consisting of a bright core, a dark cavity and a narrow, bright leading edge (Forbes 2000). About 70% of EPs are associated with CMEs and vice versa (Munro et al. 1979; Gopalswamy et al. 2003). EPs not associated with CMEs have mostly non-radial motion or are stalled by the overlying magnetic field (Gopalswamy et al. 2015). It is important to note that the association rates between these phenomena can vary significantly between studies because of different samples, projection and selection effects, as well as different detection limits of the instruments needed to identify these different phenomena (e.g., Burlespil et al. 2004; Cremades et al. 2015). The occurrence rate of solar CMEs varies in the course of the solar cycle from about one every few days in minimum to a few per day in maximum. The associated mass-loss rate ranges from about 1.5 to 4.8×10^{-16} M_⊙ yr^{-1} from minimum to maximum (Vourlidas et al. 2010), i.e. a few per cent of the average mass-loss rate from the solar wind (∼2×10^{-14} M_⊙ yr^{-1}; Wang 1998). CME masses can be up to several 10^{16} g, whereas their velocities range from a few 100 to a few 1000 km s^{-1} (Webb & Howard 2012).

It has been hypothesized that active stars with their frequent and powerful flares could also have correspondingly numerous energetic CMEs. These could be an important contribution to stellar mass- and angular momentum loss; therefore, they could strongly influence the evolution of young stars (Aarnio et al. 2012; Drake et al. 2013; Osten & Wolk 2015; Cranmer 2017). Observations of CMEs on other stars are challenging because the close stellar environment cannot be spatially resolved like in solar observations. Up to now, there are only a few cases in which stellar mass ejections have been observed. Several events were detected as transient blue-shifted emission components in spectral lines during flares (Houdebine et al. 1990; Gunn et al. 1994; Guenther & Emerson 1997; Fuhrmeister & Schmitt 2004; Leitzinger et al. 2011; Vida et al. 2016). Other indications of ejected mass during stellar flares stem from transient absorptions seen in UV or X-rays, indicating excess neutral material rising above the flaring region and obscuring the emission (Giammappa et al. 1982; Haisch et al. 1983; Ambruster et al. 1986; Doyle et al. 1988; Wheatley 1998; Favata & Schmitt 1999; Pandey & Singh 2012). However, such observations are more difficult to interpret because of the lack of information on the plasma velocity. Mass estimates of observed stellar CME events range from 10^{15} to 10^{17} g and line-of-sight velocities from ∼100 to 5800 km s^{-1}. The masses are comparable to those estimated for stellar prominences (Collier Cameron & Robinson 1989; Collier Cameron et al. 1990; Dunstone et al. 2006; Leitzinger et al. 2016), which can be observed as transient features in the broadened Balmer line profiles of fast rotating young stars. Prominences consist of cool chromospheric material and often form the cores of CMEs if they erupt, which explains why stellar mass ejection events can be observed in the Balmer lines. Another observational attempt to detect stellar CMEs is the search for radio type II bursts, which are related to propagating shock fronts and are therefore often associated with CMEs on the Sun (Reiner et al. 2001; Gopalswamy et al. 2005). However, up to now, no radio bursts of this type were detected on other stars (Leitzinger et al. 2008, 2010; Boiko et al. 2012; Crosley et al. 2016).

Previous studies aimed to establish correlations between solar flare energies and CME parameters to estimate the possible occurrence frequencies, as well as associated mass-, energy- and angular momentum loss rates on young stars (Aarnio et al. 2012; Drake et al. 2013; Osten & Wolk 2015). Leitzinger et al. (2014) used a similar approach to interpret the non-detection of mass ejections in young open cluster stars. Recently, Cranmer (2017) attempted to infer stellar CME mass-loss rates from surface-averaged magnetic fluxes. However, the question remains how reliable such estimates based on the extrapolation of the solar relations to stars with much higher activity levels are. In this study, we describe an empirical model similar to those mentioned before to address this question in more detail. In section 2, we describe the model, including similarities and differences to previous approaches. In section 3, we compare the estimated CME occurrence and mass-loss rates of active Sun-like stars with existing observations of stellar mass-loss rates. Possible limitations of such extrapolations will be discussed in section 4 and we summarize our findings in section 5.

2 MODEL DESCRIPTION

Here, we develop an empirical model with the aim to estimate stellar CME rates from combining stellar flare rates and observed flare–CME relationships from the Sun. This approach is similar to previous studies (Aarnio et al. 2012; Drake et al. 2013; Osten & Wolk 2015), but differs in that we are using purely observational relations, similar as in Leitzinger et al. (2014) and Odert (2016).

The differential distribution of flare-related CMEs as a function of their masses M can generally be written as

\[ \frac{dN}{dM} = \frac{dN}{dE_s} \frac{dE_s}{dE_{\odot}} \frac{dE_{\odot}}{dM} \frac{1}{P(M)}, \]

where N is the number of events per unit time and E_{\odot} is the stellar/solar flare energies. The first term on the right hand side is the differential distribution of stellar flares as a function of their energy. The second term accounts for the different energy bands of solar and stellar observations. The third term describes the relation between flare energy and CME mass on the Sun. The fourth term describes the probability that a flare is associated with a CME (i.e., the CME-flare association rate). We estimate each of these terms below.
2.1 Stellar flare rates

The differential distribution of both solar and stellar flares as a function of their energy is well represented by a power law

$$\frac{dN}{dE} = k_E E^{-\alpha}$$

with index $\alpha$ and constant $k_E$. Typical values of $\alpha$ range from 1.4 to 2.7 in both solar and stellar flare observations (e.g. Güdel et al. 2003, and references therein). The values show some dependence on the wavelength range and the covered flare energy range. Despite the similarities of $\alpha$ found in solar and stellar observations, the constant $k_E$ generally differs, because stars with a higher activity level have more flares of a given energy than less active stars (Gershberg 1989). Audard et al. (2000) found that the daily number of stellar X-ray flares with energies $E_X > 10^{33}$ erg is closely related with the total stellar X-ray luminosity $L_X$ via

$$\log(N(E > 10^{33}[d^{-1}]) = a + b \log L_X,$$

with $a = -26.7 \pm 2.9$, $b = 0.95 \pm 0.1$, and $L_X$ given in erg s$^{-1}$. This scaling holds for stars with $L_X \times 10^{-21}$ to $10^{31}$ erg s$^{-1}$. From Eq. 2, one can deduce an expression for the cumulative flare distribution

$$N(E) = \int_{E}^{\infty} \frac{dN}{dE'} = \frac{k_E}{a-1} E^{1-\alpha},$$

representing the number of flares above energy $E$. Comparing with Eq. 3, one can then express $k_E$ as a function of $\alpha$ and $L_X$ as

$$k_E = (a-1) 10^{2(\alpha-1)\alpha} L_X^b.$$  

This scaling allows to estimate the X-ray flare distribution of any Sun-like main-sequence star simply by its measured $L_X$ as a function of the flare power law index $\alpha$.

2.2 Conversion of energy bands

It is important to note that stellar X-ray observations are typically performed in different bands compared to solar observations. Therefore, some conversion to relate the flare energies in solar and stellar bands has to be applied. Audard et al. (2000) used a constant count-to-flux conversion factor for both flares and quiescent emission corresponding to the combined X-ray and EUV (XUV; 0.01–10 keV; 0.1–124 nm) range. However, they note that most of the energy release of their target stars occurs within 0.1–5 keV (0.25–12.4 nm), comparable to the 0.1–2 keV band of ROSAT. Comparison with ROSAT observations (Schmitt & Liefke 2004) of the stars in their sample shows that their given XUV luminosities are comparable to the X-ray values. In some cases, they are up to 0.1–0.2 dex higher, which is, however, comparable to the scatter between different ROSAT observations of the same star at different times. Thus, both the XUV luminosities and flare energies given in Audard et al. (2000) should be comparable to broad band stellar X-ray data.

On the other hand, all solar relations used here relate to measurements from the Geostationary Operational Environmental Satellite (GOES) performed in the 0.1–0.8 nm (1.55–12.4 keV) band, commonly used to classify solar flares. To convert between solar and stellar flare energies, we adopt the relation between flare fluences $F_{\text{GOES}}$ in the GOES band and $F_{\text{XPS}}$ in the XUV Photometer System (XPS) (0.1–27 nm) band found by Woods et al. (2006). $F_{\text{XPS}} = 63 \times F_{\text{GOES}}^7$. Although the XPS band is not exactly equal to that of the stellar flare study from Audard et al. (2000), it should be a reasonable proxy. Converting fluence to energy and setting $E_{\text{XPS}} = E_X$, we find

$$E_X = \eta E_{\text{GOES}}^7$$

with $\eta = 6.7 \times 10^7$ and $\xi = 0.8$. Note that $E_{\text{XPS}}$ is within less than a factor of two compared to the total 0–190 nm emission in several large solar flares (Woods et al. 2006), indicating that it is likely a good proxy for the flare energies in the XUV range.

2.3 Solar flare energy and CME mass

On the Sun, flare energies and the masses of their associated CMEs are correlated (Aarnio et al. 2012; Drake et al. 2013; Takahashi et al. 2016; Compagno et al. 2017). This is also physically plausible because the energies of CMEs and the bolometrically radiated flare energies are of similar magnitude (Emelie et al. 2012). The CME masses are related with the GOES X-ray energies of their associated flares via a power law

$$M = \mu E_{\text{GOES}}^\beta$$

with parameters $\mu = (2.7 \pm 1.2) \times 10^{-3}$, $\beta = 0.63 \pm 0.04$ (Aarnio et al. 2012) and $\mu = 10^{-1.3 \pm 0.2}$, $\beta = 0.59 \pm 0.02$ (Drake et al. 2013), respectively. The masses for both parameter sets are rather similar and deviate only for the highest masses by a factor of about two. This is negligible compared to the intrinsic spread of about an order of magnitude about this relation. Hereafter we adopt the parameters of Drake et al. (2013).

2.4 CME–flare association rate

The solar CME–flare association rate increases with flare energy. Yashiro et al. (2006) obtained an expression as a function of solar GOES flare fluence which can be written as $P(F_{\text{GOES}}) = 0.371 \log(F_{\text{GOES}}) + 3.3$. This relation is in good agreement with the more recent studies of Yashiro & Gopalswamy (2009). By converting fluence to energy as before and using Eq. 7, we can express $P$ as a function of CME mass

$$P(M) = c + d \log M$$

with $c = -9.02$ and $d = 0.63$. Equation 8 is valid between $M_1 = 8.5 \times 10^{15}$ g where $P(M_1) = 1$ and $M_0 = 2.2 \times 10^{14}$ g where $P(M_0) = 0$. For $M > M_1$, $P(M_1) = 1$, i.e. all flares are associated with CMEs. Note that Eq. 8 is strictly not valid for $P(M) \rightarrow 0$ (Yashiro et al. 2006). However, this lower cut-off is adopted here because the CME–flare association is not well established for weak flares due to the sensitivity limits of solar instruments and selection effects. Thus, $1$ Flence (J m$^{-2}$) is converted to energy at the Sun (erg) with the factor $1.406 \times 10^{10}$, which corresponds to $10^7 \times 2\pi$ AU$^2$ erg, assuming uniform radiation into the visible hemisphere of the Sun (Woods et al. 2006).
the inferred CME occurrence rates estimated here represent a lower limit. On the other hand, weak flares are typically associated with less massive CMEs (Eq. 7). Therefore, the computed mass-loss rates (section 2.7) will not be significantly by this approach. The mass limits \( M_0 \) and \( M_1 \) correspond to X-ray flare energies of \( 2 \times 10^{29} \) and \( 2.9 \times 10^{31} \) erg, as well as to GOES flare energies of \( 7.1 \times 10^{26} \) and \( 3.5 \times 10^{29} \) erg, respectively.

### 2.5 Inferred stellar CME distribution

We now determine \( dN/dM \) (Eq. 1) using Eqs. 2, 6, and 7 by evaluating all required terms and expressing them as a function of CME mass \( M \). This yields the stellar CME distribution

\[
dN/dM = P(M)k_M M^{-\gamma},
\]

where we have defined

\[
k_M = k_E \frac{\xi}{B} \gamma^{1-\alpha} \mu^{\gamma-1}, \quad \gamma = 1 - \frac{\xi(1-\alpha)}{B},
\]

with \( k_E \) from Eq. 5 and \( P(M) \) from Eq. 8. For CME masses larger than \( M_1 \), Eq. 9 yields a power law similar to the flare distribution (Eq. 2). With Eq. 9, one can deduce the CME occurrence rate for any star given its X-ray luminosity \( L_X \) and flare index \( \alpha \). The magnitude of the distribution mainly depends on \( L_X \), because \( k_M \) is a function of \( L_X \), whereas the slope is determined by \( \alpha \) if all other scaling law parameters are fixed. A typical range of \( \alpha = 1.5 \) to 2.5 translates to a range of \( \gamma = 1.67 \) to 3.03.

In Fig. 1, we show the inferred differential CME distribution of a star with \( \log L_X = 26.5 \) erg s\(^{-1} \) and four values of \( \alpha \). It is obvious that smaller values of \( \alpha \) yields a higher number of massive CMEs and a lower number of low-mass CMEs compared to larger values of \( \alpha \). Using higher values of \( L_X \) yields similar distributions, but simply shifted upwards along the \( \gamma \)-axis. We compare the results with the observed solar differential CME distribution, which was found to follow a power law for the high mass tail with an index \( \gamma = 2.1 \) (Aarnio et al. 2012). Using Eq. 9, we can reproduce this slope using a broad-band X-ray flare index \( \alpha = 1.8 \). This index is in good agreement with solar flare observations (Hudson 1991) and the distribution of thermal energies (Aschwanden et al. 2015). Thus, we conclude that the power law indices used in the individual scalings entering Eq. 9 are reasonable. For the highest masses, the observed slope is slightly steeper than predicted and follows the \( \alpha = 2.5 \) curve. This may be due to either the exponential cut-off in flare energies discussed in section 4, i.e. a steepening of the real flare distribution close to the largest flare energies, or the small number of observed CME events in these bins. The adopted X-ray luminosity of \( \log L_X = 26.5 \) erg s\(^{-1} \) is close to the value estimated for solar minimum conditions in the ROSAT band (Peres et al. 2000).

### 2.6 Occurrence rates

To obtain the occurrence rate of CMEs above a certain mass \( M \), one can construct the cumulative distribution from Eq. 9,

\[
N(>M) = \int_{M}^{\infty} \frac{dN}{dM} dM' =
\]

\[
= \begin{cases} 
\frac{k_M M^{1-\gamma}}{(\gamma-1)^2 \ln(10)} (M_1^{1-\gamma} - M_1^{1-\gamma}) & \text{for } M \geq M_1 \\
+ \frac{k_M}{\gamma} M^{1-\gamma} P(M) & \text{for } M_0 < M < M_1.
\end{cases}
\]

The cumulative number evaluated at the minimum considered CME mass \( M_0 \) represents approximately the total number of CMEs per unit time. However, the cumulative distribution slightly overestimates the total CME rate because the integration goes to infinity. This overestimate is higher for smaller \( \alpha \). However, there likely is an upper limit to possible CME masses for any given star, similar to the maximum possible flare energy (Aulanier et al. 2013). Thus, in order to obtain a better estimate of the total CME rate, we integrate Eq. 9 between \( M_0 \) and a maximum expected CME mass \( M_{max} \).

\[
N = \int_{M_0}^{M_{max}} \frac{dN}{dM} dM =
\]

\[
= \begin{cases} 
\frac{k_M}{\gamma-1} \left[ \frac{d}{\ln(10) \gamma} (M_1^{1-\gamma} - M_1^{1-\gamma}) - M_1^{1-\gamma} \right] & \text{for } M_{max} \geq M_1 \\
+ \frac{k_M}{\gamma} \left[ \frac{d}{\ln(10) \gamma} (M_1^{1-\gamma} - M_1^{1-\gamma}) - M_1^{1-\gamma} P(M_{max}) \right] & \text{for } M_0 < M_{max} < M_1 \\
0 & \text{for } M_{max} \leq M_0.
\end{cases}
\]

This result is valid for \( \gamma \neq 1 \). Since \( \gamma = 1 \) would require \( \alpha = 1 \) (cf. Eq. 10), which is lower than observed for both the Sun and stars, we only give the solution above. We estimate \( M_{max} \) from the maximum expected flare energies using Eqs. 7 and 6, where the maximum flare energies are estimated as \( E_{max} \approx 10^{4.5} L_X \). This corresponds roughly to the largest observed flare energies in the stellar sample of Audard et al.
\[ M_{\text{max}} = \log \left( \frac{10^{4.5}}{\eta} \right)^{\beta/\xi} + \frac{\beta}{\xi} \log L_X \approx -3.955 + 0.7375 \log L_X. \]  

This scaling yields maximum possible CME masses in the order of \(10^{13}\) to \(10^{18}\) g for stars with \(L_X \approx 10^{26}\) to \(10^{30}\) erg s\(^{-1}\). Using Eq. 12, we calculate the total number of CMEs per day as a function of \(L_X\) and \(\alpha\) (Fig. 2), in comparison to the cumulative rates from Eq. 11. The occurrence rate increases with both \(L_X\) and \(\alpha\). One can see that there is a very large spread for our adopted range of \(\alpha\) by more than two orders of magnitude. This indicates that such a scaling is only useful for stars for which \(\alpha\) has been determined with high accuracy. The cumulative rate generally gives a good approximation to that calculated with \(M_{\text{max}}\) for most of the parameter space. It predicts slightly higher rates for stars with low \(L_X\) and small \(\alpha\).

### 2.7 CME mass- and energy loss rates

The mass-loss rate due to CMEs can be calculated via

\[
\dot{M} = \int_{M_0}^{M_{\text{max}}} M \frac{dN}{dM} dM = \int_{M_0}^{M_{\text{max}}} P(M) k_M M^{-\gamma+1} dM
\]

\[
= \left\{ \begin{array}{ll}
\frac{k_M}{\gamma - 2} & \frac{d}{(\gamma - 2) \ln(10)} \left( M_0^{2-\gamma} - M_1^{2-\gamma} \right) - M_0^{2-\gamma} M_{\text{max}}^{2-\gamma} \\
& \text{for } M_{\text{max}} \geq M_1 \\
\frac{k_M}{\gamma - 2} & \frac{d}{(\gamma - 2) \ln(10)} \left( M_0^{2-\gamma} - M_{\text{max}}^{2-\gamma} \right) - M_{\text{max}}^{2-\gamma} P(M_{\text{max}}) \\
& \text{for } M_0 < M_{\text{max}} < M_1 \\
0 & \text{for } M_{\text{max}} \leq M_0
\end{array} \right.
\]

(14)

Figure 2. Total number of CMEs per day as a function of \(L_X\) and \(\alpha\). Solid lines indicate rates with integration up to a maximum CME mass, whereas dashed lines show the occurrence rates derived from the cumulative distribution.

Figure 3. CME mass-loss rates as a function of \(L_X\) and \(\alpha\). The relation from Drake et al. (2013) is shown as a dashed line; it has almost negligible dependence on \(\alpha\).

\[ \dot{M} \approx \frac{k_M}{\gamma - 2} \frac{d}{(\gamma - 2) \ln(10)} \left( M_0^{2-\gamma} - M_1^{2-\gamma} \right) - M_0^{2-\gamma} M_{\text{max}}^{2-\gamma} \]

if \(\gamma \neq 2\). For \(\gamma = 2\) (corresponding to \(\alpha \approx 1.74\)), the solutions are

\[
\begin{align*}
&\left\{ \begin{array}{ll}
\frac{k_M}{\gamma - 2} & \frac{d}{(\gamma - 2) \ln(10)} \left( M_0^{2-\gamma} - M_{\text{max}}^{2-\gamma} \right) - M_{\text{max}}^{2-\gamma} P(M_{\text{max}}) \\
& \text{for } M_0 < M_{\text{max}} < M_1 \\
0 & \text{for } M_{\text{max}} \leq M_0
\end{array} \right. \\
& \text{for } M_{\text{max}} \geq M_1
\end{align*}
\]

(15)

The resulting CME mass-loss rates are shown in Fig. 3. The mass-loss rates increase with \(L_X\) and \(\alpha\). As a comparison, we also plot the relation derived by Drake et al. (2013). Their result shows a steeper dependence on \(L_X\) than ours, and their dependence on \(\alpha\) is almost negligible. Despite being quantitatively similar to our results for intermediate \(L_X\), their predicted mass-loss rates are lower (higher) for less (more) active stars. These differences are likely caused by the different method used to calculate \(\dot{M}\). Specifically, we find that their weak dependence on \(\alpha\) results from their approach to calculate \(k_E\), by setting the flare power in the integration range equal to \(L_X\).

We can also estimate the kinetic energy loss rates \(E_{\text{kin}}\) due to CMEs. The kinetic energies of solar CMEs also scale with the energies of the corresponding flares

\[ E_{\text{kin}} = \epsilon E_{\text{GOES}}^\delta \]

(Drake et al. 2013), where \(\epsilon = 10^{0.81 \pm 0.85}\) and \(\delta = 1.05 \pm 0.03\). The kinetic energy loss rate has the same form as Eqs. 14 and 15, but \(\mu\) and \(\beta\) have to be replaced with \(\epsilon\) and \(\delta\) in Eq. 10. Furthermore, we transform the flare–CME association rate (Eq. 8) \(P(M) \rightarrow P(E_{\text{kin}})\) and find the corresponding parameters \(c = -10.25\), \(d = 0.35\), \(E_{\text{kin},0} = 10^{29}\) and \(E_{\text{kin}} = 6.8 \times 10^{31}\) erg. The resulting kinetic energy loss rates are shown in Fig. 4. To estimate \(E_{\text{kin,max}}\), we use Eqs. 16, 6, and the maximum flare energy estimate from section 2.7.

For the most active stars with \(L_X = 10^{39}\) erg s\(^{-1}\), \(E_{\text{kin}}\) is about 0.1–0.4 per cent of the solar bolometric luminosity, depending on \(\alpha\). This is lower than the value of 1 per cent found by Drake et al. (2013) for the same \(L_X\). Note also that for the
highest \(L_X\), \(\dot{E}_{\text{kin}}\) is higher for smaller \(\alpha\), in contrast to the behavior of \(M\).

### 2.8 Collision rate with planets

An important application of such empirical CME models is the estimation of impact rates on orbiting planets, which can inform us about expected “Space Weather” effects in exoplanet systems. The impact frequency \(f_{\text{imp}}\) can be written as

\[
f_{\text{imp}} = P_1 P_2 f_{\text{CME}}
\]  

(Khodachenko et al. 2007a), where \(f_{\text{CME}}\) is the intrinsic stellar CME rate and \(P_1, P_2\) the meridional and azimuthal impact probabilities, respectively,

\[
P_1 = \frac{\sin[(\Delta + \delta_{\text{pl}})/2]}{\sin \Theta}, \quad P_2 = \frac{(\Delta + \delta_{\text{pl}})}{2\pi},
\]

where \(\Delta_{\text{CME}}\) is the angular width of the CME, \(\delta_{\text{pl}}\) is the angular width of the planet as seen from the star, and \(\Theta\) is the maximum stellar latitude of CMEs (i.e., CME source locations are within \(\pm \Theta\)). The planet is assumed to orbit in the stellar equatorial plane. All angular quantities are given in radians. Note that \(P_1 = 1\) if \(\Theta < (\Delta + \delta_{\text{pl}})/2\). To estimate the impact rate resulting from the distributions calculated before, we need to transform the mass-dependent occurrence rate (Eq. 9) into one depending on angular width. On the Sun, there is a correlation between the apparent angular widths (width projected onto the plane-of-sky) and masses of CMEs (Gopalswamy et al. 2005; Aarnio et al. 2011). We use the relation of Gopalswamy et al. (2005),

\[
\log M = 12.6 + 1.3 \log \Delta_{\text{app}}
\]

where \(M\) is in grams and the apparent width \(\Delta_{\text{app}}\) in degrees. This relation was calibrated for CMEs with apparent widths \(\leq 120^\circ\). The total impact rate is thus

\[
f_{\text{imp}} = \int_{\Delta_0}^{\Delta_{\text{max}}} P_1 P_2 \frac{dN}{dM} \frac{dM}{d\Delta_{\text{app}}} \frac{d\Delta_{\text{app}}}{d\Delta_{\text{true}}} d\Delta_{\text{true}},
\]

where \(dN/dM\) is taken from Eq. 9 and \(dM/d\Delta_{\text{app}}\) can be derived from Eq. 19. We introduce a correction factor \(d\Delta_{\text{app}}/d\Delta_{\text{true}}\), which accounts for the fact that the impact rate depends on the true angular widths of the CMEs. Equation 19 relates the masses only with the apparent widths from observations, which are affected by projection effects. Solar CMEs appear systematically larger if they are not propagating in the plane-of-sky and their true widths depend on their source locations and their direction of propagation, so there is no unique transformation between these quantities. Overestimated angular widths would lead to overestimated impact rates. We apply a correction of this effect using the observed and true distributions of solar CME widths (Wu & Chen 2011). By forward modeling of a large sample of artificial CMEs and applying projection effects, these authors obtained distributions of the apparent CME parameters. Those were then compared with observations to infer the underlying true distribution. We calculate \(|d\Delta_{\text{app}}/d\Delta_{\text{true}}| = f(\Delta_{\text{true}})/f(\Delta_{\text{app}})\) using Eqs. 2 and 9 from Wu & Chen (2011). We then integrate Eq. 20 between \(\Delta_0 \approx 20^\circ\) corresponding to \(M_0\) and \(\Delta_{\text{max}}\), which we choose to be 180\(^\circ\), but the inferred impact rates are not very sensitive to the exact upper limit.

The resulting CME impact rates on a planet are shown in Fig. 5. As the angular size of a planet is typically very small compared to that of a CME for a wide range of orbital distances, including the location of the HZs of F–M stars, we simply set \(\delta_{\text{pl}} \approx 0\). The impact rates are shown as a function of \(L_X\) and \(\alpha\). We adopted \(\Theta = 90^\circ\), which may underestimate the impact rate for stars with CME locations preferentially at low latitudes, but overestimates the rates for stars where CMEs occur mainly near the polar regions. However, this choice varies the impact rates by less than a factor of two, which is small compared to the spread of almost three orders of magnitude for different choices of \(\alpha\). Note that ignoring the correction factor \(d\Delta_{\text{app}}/d\Delta_{\text{true}}\) would increase the resulting impact rates by factors of 2–4 for \(\alpha\) of 2.5–1.5, independent of \(L_X\). For the Sun (adopt-
ing $\alpha = 1.8$), we find $N_{\text{imp}}$ of about 10–100 per year for the range of $L_X = 2.7 \times 10^{26} - 4.7 \times 10^{27} \text{erg s}^{-1}$ from Peres et al. (2000), which is roughly in the order of front-sided Halo CMEs and geoeffective CMEs during the solar cycle (Wang et al. 2002). Note that in the solar system about 40–70 per cent of Earth-directed Halo CMEs are geoeffective (Wang et al. 2002; Gopalswamy et al. 2007). Thus, we conclude that the results are reasonable, despite ignoring many details of CME propagation like non-radial motion, deflection (thoroughly discussed in Kay et al. 2016), shape, and magnetic field orientation (e.g. Kim et al. 2008). Note that the estimated ratio of CME impacts to intrinsic injections is about 2–4 per cent, very similar to the ratio of Halo CMEs to all CMEs of 3.6 per cent on the Sun (Gopalswamy et al. 2007).

Depending on the typical duration of CMEs, young planets orbiting active stars may be under constant solar wind exposure, thus mimicking a faster, denser stellar wind that may lead to increased ion pick-up loss rates (Khodachenko et al. 2007a, b; Kislyakova et al. 2013, 2014). This occurs if $N_{\text{imp}} \tau > 1$, where $\tau$ is the typical duration of a CME (Khodachenko et al. 2007a). For the Sun, $\tau \approx 8$ h at $6$–$10$ $R_\odot$, but this number can either increase or decrease with distance from the Sun (Lara et al. 2004). It is a lower limit, since it is only measured for the leading edge. In comparison, the durations of magnetic clouds at $1$ au are on average $19$–$22$ h, with maximum values up to $48$ h (Gopalswamy et al. 2015). However, at $1$ au they already have dimensions of about $0.2$ au, which explains their longer duration. To fully recover from the passage of a CME, the interplanetary medium needs about $2$–$5$ d (Temmer et al. 2017). We plot limits for different $\tau$ from $8$ to $24$ h in Fig. 5, because cooler stars have closer HZs and possibly shorter $\tau$ than magnetic clouds (MCs) at $1$ au. For $N_{\text{imp}} > 1/\tau$, a planet in the HZ would be exposed to a permanent CME wind. Khodachenko et al. (2007a) estimated ion pick-up loss rates for a ‘Hot Jupiter’ ranging from $1.5 \times 10^{11}$ to $9.5 \times 10^{16} \text{g s}^{-1}$, depending on the CME density and velocity at the planet’s orbit, as well as the planetary magnetic moment, assuming such permanent CME exposure. In the HZs of M dwarfs ($<0.2$ au), oxygen ion loss rates from CO$_2$-rich planets of up to several tens of bar per Gyr for non-magnetized, and a few bar per Gyr for magnetized planets were estimated (Lammer et al. 2007). For a closer distance of $0.05$ au, the loss rates increase up to $10^4$ bar per Gyr for the non-magnetized, and a few $100$ bar per Gyr for the magnetized case. This demonstrates the importance of better understanding stellar CME activity, because of the huge potential impact on planetary atmosphere evolution.

### 3 COMPARISON WITH OBSERVATIONS

For applying the empirical model to younger and more active stars, the question remains if there is a limit where the predicted results may not be realistic anymore. Since application to active stars requires extrapolation of the solar relations to higher flare energies/CME masses and to stars becoming increasingly non-Sun-like (the same holds for extrapolation to other spectral types, e.g. M dwarfs), it is possible that at some point the adopted scalings may not be valid anymore. Here we attempt to find some observational constraints which could be used to test the predictions of our model.

#### 3.1 Testing the model with solar observations

First, we compare the model results with solar observations. Since the model also includes relations derived from active stars (Audard et al. 2000), it could be possible that our model does not properly predict CME rates of older, rather inactive stars, like the Sun itself. However, as shown before (Fig. 1), the observed solar CME distribution (Aarnio et al. 2012) can be well reproduced with our model if choosing $\alpha = 1.8$ and $L_X = 26.3 \text{erg s}^{-1}$. Using the minimum-to-maximum range of the solar X-ray luminosity of $2.7 \times 10^{26}$ to $4.7 \times 10^{27} \text{ erg s}^{-1}$ (Peres et al. 2000) together with Eq. 12 to estimate the number of CMEs per day yields 0.7 and 13 for solar minimum and maximum, respectively (for $\alpha = 1.8$). Our estimate for the maximum is about a factor of 2–3 higher than the average daily rates from observations in the course of the solar cycle (depending on either manual or automated detection techniques; Yashiro et al. 2008), but on individual days such high numbers have been observed (Gopalswamy et al. 2009a; Bilenko 2014). Since the adopted solar values of $L_X$ also correspond to short snapshots of the solar emission rather than long-term averages, we find that the agreement is reasonable. Using Eq. 14, we find a CME mass-loss rate of $1.3 \times 10^{-16}$ to $5.5 \times 10^{-15} \text{ M}_\odot \text{ yr}^{-1}$, i.e. about 0.7 to 27 per cent of the total solar mass-loss rate ($M_\odot \times 2 \times 10^{-14} \text{ M}_\odot \text{ yr}^{-1}$; Wang 1998). Our results are in agreement with observations, indicating a contribution of a few per cent (Vourlidas et al. 2010), although our maximum value is again higher. For the solar kinetic energy loss rates, we find $3.6 \times 10^{-9}$ to $6.3 \times 10^{-7} \text{ L}_\odot$. This corresponds to about 5 to 50 per cent of the coronal radiative energy loss rate $L_X$. The average kinetic energy loss rate from observations is in the order of $10^{-7} \text{ L}_\odot$ (Vourlidas et al. 2010), in agreement with our results.

#### 3.2 Comparison with observed stellar mass-loss rates

Measurements of stellar mass-loss rates provide an upper limit for the mass-loss rates through CMEs, since the latter cannot be higher than the total mass-loss rates from observations. Therefore, comparison of our results with observations can be used to test the extrapolation to active stars. On the Sun, the contribution of CMEs to the total mass-loss is in the order of a few per cent (Vourlidas et al. 2010). If CMEs occur only sporadically, their contribution to stellar mass-loss will also be negligible, like on the Sun, and mass-loss will be dominated by the steady wind. For very active stars, CMEs may occur so frequently that, as an ensemble, they mimic an almost steady wind driven by continuous eruptions. In this case, the related mass-loss rates could be so high that CMEs may be the dominant source of mass-loss. Theoretical stellar wind models suggest that a young Sun-like star at an age of about 100 Myr could have wind-driven mass-loss rates of several $10^{-14}$ to $10^{-13} \text{ M}_\odot \text{ yr}^{-1}$ (depending on its rotation rate), i.e. only up to about 10 times higher than the present Sun (Johnstone et al. 2015a,b). In comparison, estimated CME mass-loss rates could be $10^{-12}$ to $10^{-11} \text{ M}_\odot \text{ yr}^{-1}$ for such a star (Fig. 3).
Several attempts to measure mass-loss rates of cool main-sequence stars have been made. Maximum possible rates were estimated by Lim & White (1996), who argue that observation of non-thermal coronal radio emission in young stars places an upper limit of about $10^{-15} \, M_\odot$ yr$^{-1}$ on any ionized circumstellar material. An additional constraint is the fact that any potential emission from a dense wind cannot exceed observed fluxes in X-rays to UV. Moreover, X-ray and EUV observations towards active stars do not indicate abnormal column densities, which provides an additional upper limit to any neutral circumstellar material (van den Oord & Doyle 1997). Thus, mass-loss from active cool stars should be too small and thus difficult to detect. These upper limits are comparable to the maximum CME-related mass-loss rates we obtain here for our most active stars. This indicates that it is unlikely that we underestimate the CME rates with our approach, also justifying to ignore potential CMEs that are not related to flares.

Other methods, including the search for free-free emission from fully ionized winds (Lim et al. 1996; Gaidos et al. 2000; Gudel 2002; Fichtinger et al. 2017) or charge exchange X-ray emission at the astropause (Wargelin & Drake 2001, 2002), provided further upper limits of similar order of magnitude. However, the detection of excess absorption in Ly$\alpha$ by hot neutral hydrogen, which is produced at the astropause by charge exchange of the stellar wind and the interstellar medium, provided the first actual observations. Mass-loss rates have been derived for about a dozen of cool stars with this method (Wood et al. 2001, 2002, 2005b, 2014). The presently available Ly$\alpha$ data suggest a maximum mass-loss rate of about $100 \, M_\odot$ for Sun-like and cooler main-sequence stars. This maximum is obtained for moderately active stars, however, even more active stars seem to have much smaller mass-loss rates than suggested by the increase from inactive to moderately active stars.

Recently, yet another method to probe tenuous stellar winds has emerged. Close-in exoplanets can act as a probe of the local stellar wind conditions. By modeling the exoplanet’s evaporating atmosphere causing excess Ly$\alpha$ absorption during transits, Vidotto & Bourrier (2017) determined the stellar wind parameters of the nearby M dwarf GJ 436b, based on Bourrier et al. (2016). They estimated mass-loss rates of 0.5 to $2.5 \times 10^{-15} \, M_\odot$ yr$^{-1}$. As before, the method is not able to distinguish between CMEs and the steady wind, so the inferred mass-loss rates will include both contributions.

In Fig. 6, we reproduce Fig. 4 of Wood et al. (2014), which shows the total mass-loss rate per unit surface area in solar units as a function of surface X-ray flux for the stars with detected Ly$\alpha$ absorption. Also shown is the proposed power law fit from Wood et al. (2014) of mass-loss rate as a function of $F_X$, valid for inactive to moderately active stars. From their data, there is a clear indication of a cut-off at $F_X \sim 10^6 \, \text{erg} \, \text{s}^{-1} \, \text{cm}^{-2}$. For more active stars, the observed mass-loss rates are much smaller than extrapolation of the power law would suggest. Furthermore, we include the mass-loss rate of GJ 436 (Vidotto & Bourrier 2017), as derived from modeling the transit observations of its exoplanet. We overplot our results from Eq. 14 for several $\alpha$ (see also Table A1), adopting both a Sun-like star (1R$\odot$, solid lines) and an M dwarf (0.3R$\odot$, dotted lines) for normalization. Our estimated CME mass-loss rates (cf. also Table A1) are generally comparable or lower than the total mass-loss rates found from Ly$\alpha$ absorption, especially for $\alpha < 2$. However, for $\alpha > 2$ our predictions are close to or above the observed rates. The agreement with observations of total mass-loss rates breaks down at the power law cut-off, as our model predicts increasing CME mass-loss rates with increasing X-ray flux. Even under the assumption that mass-loss of active stars may be dominated by CMEs, our results are inconsistent with observed mass-loss rates because there are about an order of magnitude lower than our predicted minimum values. In the framework of a steady wind, Wood et al. (2014) attempted to explain their results by a change in magnetic field topology and the emergence of polar spots which lead to a more dipole-like field. However, Vidotto et al. (2016) do not find a significant break in the magnetic field parameters at this activity level. Recent model results indicate that high-latitude spots lead to a significant reduction of stellar mass- and angular momentum loss compared with low-latitude spots or even a purely dipolar field (Garrafó et al. 2015). Linsky & Wood (2014) also offer a physical interpretation of both the relationship and its break-down. For the most active stars, they suggest that most field lines could be closed and only few open lines would be available from which winds can escape. In models of Alfvén wave-driven stellar winds, it is observed that their mass-loss rates saturate for highly active stars due to enhanced radiative losses (Suzuki et al. 2013). However, this does not yet explain why CME-driven mass-loss is also low despite the high flare rates of active stars.

We briefly note that the physical basis of a correlation between global X-ray emission and mass-loss, as proposed by Wood et al. (2002, 2005b, 2014), is debated (Holzwarth & Jardine 2007; Cranmer 2008; Cohen 2011). The latter studies argue that stellar wind is related to open magnetic flux, whereas the global X-ray emission stems predominantly from regions with closed magnetic flux and thus the mass-loss via stellar winds should be independent of activity level. From the similarity of the slopes found from our predicted CME mass-loss rates and the power law from Wood et al. (2014), it is possible that an enhanced contribution of CMEs could be partly responsible for the increasing mass-loss rates with stellar activity from low to moderately active stars. It has been shown that a higher complexity of the magnetic field leads to a reduction of the wind mass-loss rates, as well as open magnetic flux (Garrafó et al. 2016). The comparison with Ly$\alpha$ observations suggests that our predictions of CME rates may become unreliable for stars with X-ray luminosities higher than about $6 \times 10^{28} \, \text{erg} \, \text{s}^{-1}$ for G star and $5 \times 10^{27} \, \text{erg} \, \text{s}^{-1}$ for M stars. We caution that this conclusion is based on a very small sample of stars with observed mass-loss rates and the fact that the Ly$\alpha$ absorption method relies on detailed knowledge of the ISM parameters towards the stars (e.g., in a fully ionized ISM, no astrophysical Ly$\alpha$ absorption can be produced; Gudel et al. 2014), which could affect the determined mass-loss rates. However, there is a surprisingly high number of non-detections of astrophysical Ly$\alpha$ absorption for many active stars (Wood et al. 2005a, 2014), which we also show in Fig. 6 (arrows along the lower x-axis). Thus, an exclusively ISM-related effect is unlikely. If the low mass-loss rates of active stars are confirmed by more observations in the future, this would also better constrain predictions of stellar CME rates.
4 DISCUSSION

Here we discuss the limitations of our empirical CME model and its application to active stars, including possible modifications of the adopted solar relations at higher stellar activity levels.

4.1 Flare rates and flare power law index

The results shown in the previous sections have a rather strong dependence on the choice of the flare power law index $\alpha$. In the most extreme cases, mass-loss rates as well as CME occurrence rates show a spread of about two orders of magnitude for the explored range of $\alpha = 1.5$ to 2.5. Thus, constraining $\alpha$ is very important to make reliable predictions of stellar CMEs for particular stars. However, the determination of $\alpha$ can depend on the detailed method and sample sizes (D'Huys et al. 2016; Ryan et al. 2016). One thing to consider is that the flare indices found for the largest observed flares, as in the study by Audard et al. (2000), may not be representative for the whole range of flare energies used for the CME rate estimates. As discussed by Aschwanden (2007), a more likely distribution than a power law stems from the avalanche model (Lu et al. 1993) and includes an exponential factor related to some maximum cut-off energy, which is determined by the maximum amount of free magnetic energy which an active region can generate. The cumulative distribution in such a model reads $N(>E) \propto E^{-\alpha+1} \exp(-E/E_{\text{cut}})$. Thus, the distribution of the most energetic flares, which are typically observed on stars due to limited sensitivity, likely falls into the range of exponential decay. This results in measuring steeper slopes which are not representative of the distribution of less energetic flares (Aschwanden 2007). Thus, observations covering large flare energy ranges (e.g. Hawley et al. 2014) would be required to disentangle...
the power law index and the exponential cutoff. However, in many studies only up to 1–2 orders of magnitude in flare energy were covered (Audard et al. 2000).

4.2 Energy band conversion

Solar and stellar observations are typically done with very different instruments. All solar scalings used here are based on GOES flare energies, whereas the stellar flare study of Audard et al. (2000) covered a much broader energy range. Therefore, we use solar flare observations performed both with GOES and the XPS instrument covering a wider energy band to scale GOES flare energies to broad band X-rays (Woods et al. 2006). The conversion factor depends on flare energy and is smaller for higher and larger for lower flare energies. It is calibrated in an energy range of \( E_{XPS} \approx 10^{30} \) to \( 3 \times 10^{32} \) erg or \( E_{GOES} \approx 10^{38} \) to \( 7 \times 10^{39} \) erg and is higher in this range (45–170) than the constant conversion factor of about 15 used in Leitzinger et al. (2014) since it covers 0.1–27 nm. The constant factor, taken from Emslie et al. (2012), represents the energy radiated by the soft X-ray emitting plasma. It was calculated from plasma parameters obtained from the GOES data and covers similar energies (\( E_{GOES} \approx 4 \times 10^{28} \) to \( 5 \times 10^{30} \) erg). We can perform a check on the suitability of Eq. 6 by applying it to the GOES X-ray background luminosity. The solar GOES background flux ranges from \( 10^{-8} \) W m\(^{-2}\) during minimum to a few \( 10^{-6} \) W m\(^{-2}\) in maximum (Veronig et al. 2003; Winter & Balasubramaniam 2014). For instance, a range of \( 10^{-8} \) to \( 3 \times 10^{-6} \) W m\(^{-2}\) corresponds to luminosities of \( 2.8 \times 10^{22} \) to \( 8.4 \times 10^{24} \) erg s\(^{-1}\). Applying Eq. 6 yields \( 6.1 \times 10^{25} \) to \( 5.8 \times 10^{27} \) erg s\(^{-1}\), in agreement with the range of estimated solar broad band X-ray luminosities in the ROSAT band (Peres et al. 2000; Judge et al. 2003). The differences in energy bands of XPS and ROSAT could yield an overestimate of \( E_X \) if assuming \( E_X \approx E_{XPS} \), since the XPS band is wider. Conversely, this means we would underestimate \( E_{GOES} \) for a chosen \( E_X \) (cf. Eq. 6), and thus the corresponding CME mass. This would lead to an underestimate of the resulting mass-loss rate. Therefore, the predicted CME occurrence and mass-loss rates from the present study are also slightly lower than in our previous study (Leitzinger et al. 2014). A more sophisticated approach by reconstructing the expected emission in the ROSAT band for a large sample of solar flares, as done for instance in Benz & Güdel (1994), would be desirable for future studies.

Another aspect is the extrapolation of Eq. 6 to flare energies larger than in solar observations. A large flare on the active RS CVn star AR Lac was observed with BeppoSAX (Rodonò et al. 1999). Its energy in the band covered by the Low Energy Concentrator Spectrometers (LECS; 0.1–10 keV) was \( 1.6 \times 10^{35} \) erg, in that of the Medium Energy Concentrator Spectrometers (MECS; 1.7–10 keV) it was \( 8.9 \times 10^{34} \) erg. Since MECS covers a similar energy range as GOES (1.5–12 keV) and we roughly assume that the ROSAT band is comparable to (LECS – MECS), this would indicate that \( E_{ROSAT} \approx E_{GOES} \) at these flare energies. Using Eq. 6 we obtain \( E_X \approx E_{ROSAT} \approx E_{GOES} \). This factor may partly be due to the larger flare energy, but also to the wider band of XPS compared to ROSAT. For given \( E_X \), this would lead to an underestimate of the corresponding CME mass by a factor of three at those energies.

4.3 CME mass–flare energy relation

There are several possibilities why the CME scalings derived here may become invalid if extrapolated to more active stars. One point is that the solar relation between CME masses and flare energies may break down for events stronger than seen on the Sun.

Leitzinger et al. (2014) briefly compared the mass estimates of stellar mass ejection events and the estimated X-ray energies of their associated flares with the solar scaling. We extend their comparison here. Specifically, we consider the events observed as blue-shifted extra-emissions in Balmer lines on the active M dwarfs AD Leo (Houdebine et al. 1990), AT Mic (Gunn et al. 1994), V374 Peg (Vida et al. 2016) and the pre-main sequence star DZ Cha (Guenther & Emerson 1997). Published estimates of their minimum masses are \( 7.7 \times 10^{17}, \sim 10^{15}, \sim 10^{16}, \) and \( 1.4 \times 10^{18} \ldots 7.8 \times 10^{19} \) g, respectively. Since no simultaneous X-ray observations of the associated flares are available, we estimate the corresponding X-ray flare energies based on the assumption that the published U-band energies are of comparable magnitude (cf. Hawley & Pettersen 1991). Doing so, we find \( E_X \approx E_U \sim 2 \times 10^{32} \) erg for AD Leo (Rodono et al. 1985; Hawley & Pettersen 1991), \( 3 \times 10^{31} \) erg for AT Mic (Gunn et al. 1994), and \( 1.2 \ldots 2.5 \times 10^{35} \) erg for DZ Cha (Guenther & Emerson 1997), respectively. The recently published event at V374 Peg has an H\,\gamma flare energy of \( 4 \times 10^{30} \) erg, which corresponds to \( 10^{32} \) erg in X-rays (Butler et al. 1988). We add two other events, which are, however, more uncertain in their interpretation as real CME events. Doyle et al. (1988) observed a strong increase in neutral hydrogen column density during a flare on the active M dwarf YZ CMi, which may be interpreted as a rising filament obscuring parts of the flare region. The estimated mass of this event is \( 3 \times 10^7 \) g and the estimated X-ray flare energy \( E_X \approx E_U \sim 8 \times 10^{30} \) erg, since the observed X-ray flare emission was likely partly absorbed by the neutral material (Doyle et al. 1988). The second one is a long-decay flare on the young, active M dwarf AU Mic, which was interpreted as an eruptive event with a CME mass in the order of \( 10^{30} \) g by Cully et al. (1994). However, there is a different model of this strong flare (\( 3 \times 10^{35} \) erg) including post-eruptive energy release, which does not involve a CME (Katsova et al. 1999). Other studies which observed stellar CME events (cf. section 1) did not provide mass estimates and had to be excluded.

We plot the estimates of stellar CME masses and X-ray flare energies in Fig. 7, in comparison with the empirical CME mass-flare energy scaling from the Sun (Eq. 7) converted to broad band X-rays using Eq. 6. For all stellar CME mass and flare energy estimates we plot error bars of an order of magnitude, comparable to quoted uncertainties of the masses. For the X-ray flare energies, this is due to the lack of direct measurements. The extrapolated scaling and the stellar observations agree to within an order of magnitude. Moreover, we show the range of typical energies of stellar prominences of a few \( 10^{16} \) to \( 10^{26} \) g (Collier Cameron & Robinson 1989; Dunstone et al. 2006; Leitzinger et al. 2016), together with the largest observed X-ray flare energies of these stars. These are in the order of \( 10^{24} \) to \( 10^{30} \) erg for the rapidly rotating, active K dwarfs AB Dor (Audard et al. 2000) and Speedy Mic (Küster 1994). One can see that this parameter space is also consistent with the ex-
For increasing $\alpha$, the difference in kinetic energy loss rates decreases. For $\alpha = 2.5$ and low $L_X$, the difference is about a factor of two, but approaches zero for large $L_X$.

This raises the question of the maximum possible flare energy which a star can produce. This quantity can be estimated as $E_{\text{flare}} \approx f E_{\text{mag}} = f (B^2 L^3) / (8 \pi) = f (B^2 A^{3/2}) / (8 \pi)$ (Aschwanden 2007; Shibata et al. 2013), where $f$ is the fraction of the free magnetic energy $E_{\text{mag}}$ that can be converted into heating (about 10 per cent), $B$ is the magnetic field strength of the active region producing the flare, and $L$ and $A$ are the active region size and area. The maximum flare energy of the Sun is estimated to be about $6 \times 10^{33}$ erg, but it may be in the order of $10^{36}$ erg for the most active stars (Aulanier et al. 2013). Deriving stringent limits for any star is limited by uncertainties in the maximum field strengths of stellar spots and their sizes. Magnetic fields are in the order of a few kG and maximum areas can be up to a few tens of percent of the stellar surface (Berdyugina 2005). Determination of stellar spot sizes is difficult because of limited spatial resolution achieved by current Doppler maps and the degeneracy between spot sizes and temperatures. Jackson & Jeffries (2013) estimated active region sizes of young M dwarfs by light curve modeling and found mean scales between individual regions of about 25 Mm. Taking this value as a maximum length scale of an individual region and assuming a maximum magnetic field strength of 5 kG (Berdyugina 2005), the maximum flare energy is in the order $10^{35}$ erg, comparable to broad band optical flare energies (Hawley et al. 2014). For stars with transiting exoplanets, spot crossings can be used to infer spot sizes, which yielded spot sizes of 40–150 Mm for a solar-like G7 star (Silva-Valio et al. 2010). This would yield maximum flare energies of $6 \times 10^{33}$ to $3 \times 10^{35}$ erg, the lower value being comparable to that estimated for the Sun.

The maximum attainable flare energy would also be related to a maximum possible CME mass, since also the kinetic energy of CMEs cannot be arbitrarily high. Detailed studies of the energetics of eruptive solar flares found that the total radiated flare energy was about one third of the total energy of the associated CME, which is in turn dominated by its kinetic energy (Emslie et al. 2004, 2005, 2012). A rough estimate of the maximum CME mass can be done by equating the maximum flare energies derived above with the kinetic energy of the CME and assuming a velocity comparable to the stellar escape velocity. This yields a maximum CME mass in the order of $10^{15}$ g for a flare energy of $10^{33}$ erg and an escape speed of 600 km s$^{-1}$ for active M dwarfs, comparable to our estimates in section 2.7. Another important point related to the power law index $\alpha$ is that it also depends on the energy range of the radiation in which the flares are observed (Güdel et al. 2003). Our empirical model is related to broad band soft X-ray emission, as frequently used for stellar flare observations, and thus we explore the typical ranges of $\alpha$ in this energy range (Audard et al. 2000). Moreover, in the optical, $\alpha$ seems to depend on the effective temperature of the star (Pettersen et al. 1984).

### 4.5 Association rate

What could actually reduce the expected high mass- and energy loss rates for the most active stars is a modification of the flare–CME association rate. Drake et al. (2013) sug-

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**Figure 7.** Relation between flare energy and CME masses from Eqs. 7 and 6. The gray shaded area indicates the range of solar data used to calibrate Eq. 7, converted to $E_X$ using Eq. 6. Black dots denote observed stellar flare energies and minimum masses of the associated CMEs, gray dots are uncertain events. The square shaded area (dashed outline) shows the range of typical prominence masses of young stars, together with the maximum flare energies observed on them.
gested a possible drop in association rate for the highest flare energies. However, this raises the question on the physical processes generating the most powerful flares on stars. Since on the Sun the probability that a flare is eruptive generally increases with increasing flare energy, the process generating the most powerful flares is likely to be closely connected with eruptive structures. We favor an alternative explanation. It is possible that the flare–CME association rate shifts to higher flare energies, meaning that it could have a similar functional form as on the Sun, but the flare energy where the association becomes about 100 per cent is much higher. In this context, it is necessary to review what is known about the differences of confined and eruptive flares on the Sun (e.g. Janvier et al. 2015).

### 4.5.1 Solar confined and eruptive flares

Flares without associated CMEs can be divided into two classes: first, there are truly confined flares which have no large-scale restructuring of magnetic fields and are typically weak, such as simple loop flares or emerging flux flares; second, flares with failed eruptions which are produced like eruptive flares, but the material falls back towards the Sun, or is caught in the overlying magnetic field (Sun et al. 2015; Mrozek 2011). Also partial eruptions have been observed on the Sun, where either only a part of a magnetic structure erupts, or some material of an eruption is partly falling back to the surface (Christian et al. 2015). Two magnetic forces are involved in an eruption: the magnetic tension of the overlying coronal field (directed inward) and the magnetic pressure of the flux rope (directed outward). As stated previously, the probability of an association with a CME increases with flare energy (Harrison 1995; Andrews 2003; Yashiro et al. 2005, 2006; Yashiro & Gopalswamy 2009). However, in 2014, one of the largest solar active regions (ARs) since 1990 (AR 12192) did not produce any CME from its core region, despite being an efficient emitter of numerous and strong flares, including many X-class flares (Sun et al. 2015; Chen et al. 2015). Thus, while the increasing association rate for stronger flares may be representative on a statistical basis, some individual active regions seem to deviate from this average picture. Possible reasons for the confined nature of strong flares can be either weak non-potentiality of the active region and/or strength and decay of the background magnetic field (Sun et al. 2015; Thalmann et al. 2015).

Comparative studies of confined and eruptive flares of similar magnitude also identified additional aspects. Confined flares are often located much closer to the active region centers, whereas eruptive flares occur closer to the borders (Wang & Zhang 2007; Cheng et al. 2011). This may, however, be directly related to conditions in the overlying field, since Cheng et al. (2011) also found that the transverse field was stronger over the active region center than at its borders. These findings agree with previous studies of Wang & Zhang (2007), who noted that the ratio of low to high coronal magnetic flux above an active region is generally larger for eruptive flares. On the other hand, the magnetic flux of the source region itself was similar for eruptive and confined flares in their study, which were all of similar magnitude. Asymmetric overlying fields seem to confine eruptions better than symmetric ones (Liu et al. 2009). Failed eruptions of ten occur in the largest active regions with stronger magnetic flux (Ji et al. 2003; Liu 2008). Liu et al. (2016) compared the properties of productive ARs (producing flares and/or CMEs) with inert ARs and found that productive ARs are always large and have sufficient free energy, but an eruptive region requires additionally a mature sheared or twisted core field or a weak overlying field.

Also theoretical studies support the picture that a steep decrease of the overlying field is necessary to produce successful eruptions. The onset of torus instability occurs only if the decay index of the overlying field is larger than about 1.5 (Török & Kliem 2005; Zuccarello et al. 2015). Observations of a filament which underwent five failed eruptions and only (partly) erupted at the sixth attempt showed that for almost similar coronal confinement in all cases, the eruption was associated with the most powerful flare which was able to supply more kinetic energy to the filament as in the failed events (Shen et al. 2011). This supports the picture that for almost constant conditions of the overlying field, the eruptiveness mainly depends on flare energy. During the solar cycle, the CME rate is generally correlated with the sunspot number, i.e. the number of active regions, but is also affected by the strength and structure of the global magnetic field (Bilienko 2014). A weakened polar field emerging in cycle 24 is the likely cause of an increased CME rate per sunspot number (Petrie 2013, 2015). The importance of the overlying field related to the solar flare–CME association rate was stressed by Hassanin & Kliem (2016), who state that the smallest eruptive flares (B) and the strongest confined flares (X) on the Sun have energies which differ by several orders of magnitude. In summary, all these studies indicate that both the strength of the flare and the overlying coronal magnetic field are key properties determining if a flare event is also associated with a CME.

### 4.5.2 Implications for active stars

From the discussions above it becomes clear that flare strength is only one factor which may indicate the occurrence of a CME. However, in our present model, we use the average flare–CME association rate from the Sun, which is only a function of flare energy. For the Sun, this relation is representative, since it is an average over a large number of flares from many different active regions. Other effects like the typical distribution of overlying magnetic field strengths are implicitly included. If, for instance, a flare of a given energy has a 30 per cent probability to be associated with a CME, this would mean that only in 30 per cent of ARs where such flares occur the overlying field is weak enough to allow an eruption. This poses a problem for extrapolation of Eq. 8 to other stars, especially to younger, more active ones. In the present model, extrapolation to more active stars implies that the average confinement remains similar as on the Sun. Based on the stronger large-scale magnetic fields of active stars and their different topologies (e.g. Donati & Landstreet 2009; Reiners 2012), it is likely that the typical confining fields could also be stronger. Young Sun-like stars seem to have much stronger toroidal field components than older stars, which could potentially inhibit CMEs (Vidotto et al. 2016). Moreover, active regions on young stars are likely larger and/or there are several neighboring regions so that the magnetic fields overlying the flare locations may be
highly complex. Using Eq. 8 could then lead to an overestimate of the CME occurrence rate and the corresponding mass- and energy loss rates, because the confinement is not properly scaled to more active stars.

Progress in understanding the role of the confining field can be made by further solar observations and theoretical modeling. For instance, Gibb et al. (2016) found that increased differential rotation leads to higher non-potentiality of the corona; they concluded that such stars may eject more CMEs. Since differential rotation increases with stellar effective temperature (i.e. with decreasing convection zone depth; Barnes et al. 2005; Collier Cameron 2007), this would suggest that young G-type stars could have more eruptive events than M dwarfs with similar rotation rates, which spin more rigidly. Moreover, if solar studies may, besides making progress in understanding the physics behind the eruptions, establish some observational property of flares distinguishing confined and eruptive events, such diagnostic may also be applied to stellar flare observations. For instance, Gopalswamy et al. (2009b) noted that several strong solar flares without associated CMEs also lacked metric type III bursts, which are indicators of non-thermal electrons propagating along open field lines. They concluded that in these cases the electrons could not access open field lines because of strong confinement. Further investigation of this finding could be potentially useful for stellar studies. Wang et al. (2016) found that confined flares have a stronger late-phase EUV emission\(^2\) than eruptive flares of similar magnitude, suggesting that the energy of the flux rope is transformed largely to thermal energy if it cannot escape. However, because of the difficulties to observe stellar EUV emission due to strong absorption by the interstellar medium at these wavelengths, this diagnostic is probably not very useful.

Recently, Harra et al. (2016) studied a sample of energetic solar flares, both confined and eruptive, with the aim to find some distinctive properties. The only feature they could identify is that eruptive events show dimmings in coronal lines. On the Sun, depth and slope of these dimming events are closely related with CME mass and speed (Mason et al. 2016). Future studies are needed to evaluate the applicability of this method to stellar observations. Of course, direct detection of stellar CMEs and constructing observational flare–CME relationships would be the most straightforward way to infer the intrinsic CME rates, but this requires long-term monitoring to catch sufficient events to reach statistically significant results (Leitzinger et al. 2014; Korhonen et al. 2016. Odert et al., in prep.). Besides that, the method is restricted to the most massive events that can still be observed in integrated light, which are likely rarer than events of moderate magnitude. If the intrinsic CME rates of active stars are indeed lower than expected due to strong confinement, the latter approach would become increasingly difficult. However, if flares on active stars are predominantly confined, but in the sense of triggering failed filament eruptions, these failed eruptions may be observable with dedicated monitoring. For instance, Vida et al. (2016) found, besides a mass ejection during a complex flare event on the young M dwarf V374 Peg, indications of some material falling back towards the star after the event, as well as some slowly rising material prior to the mass ejection, which they interpreted as failed eruption.

### 4.5.3 Estimating the effect of coronal confinement

Estimating how the changing coronal confinement would impact the flare–CME association rate, and therefore the CME occurrence rate, is difficult. To make some crude estimate, we consider a simplified toy model with an association rate described by a step function. Above a certain flare energy \(E_{\text{crit}}\), all flares should be accompanied by CMEs and below, all flares should be confined. This is equivalent of assuming a single value for the typical overlying field strength, so that the eruptiveness of a given flare is only a function of its energy for a given star. According to Wang & Zhang (2007), the ratio of low to high coronal magnetic field \(\Phi_{\text{low}}/\Phi_{\text{high}}\) above an AR must exceed a critical value for a successful eruption. We assume that this should be similar on other stars, if eruptive flares are produced by the same physical process. Then eruptive events require \(\Phi_{\text{low}}/\Phi_{\text{high}}\geq \Phi_{\text{low}}/\Phi_{\text{high}}\), where the latter ratio denotes the critical value from the Sun. Rewriting this expression yields \(\Phi_{\text{low}}/\Phi_{\text{high}}\geq \Phi_{\text{low}}/\Phi_{\text{high}}\). One can see that if the confining field in the higher corona is stronger than on the Sun, the magnetic flux at lower heights must increase accordingly.

For simplicity, we assume that the overlying field is well represented by the global coronal magnetic field of the star. This neglects possible local enhancements due to the presence of nearby ARs, as well as the flare-producing AR itself. The magnetic field strength at a distance \(r\) from the center of the star is given by

\[
B(r) = B_0 \left( \frac{R_0}{r} \right)^n ,
\]

(21)

where \(B_0\) is the photospheric magnetic field strength and \(n = 3\) for a dipolar field. The photospheric magnetic flux \(\Phi_0 = 4\pi R_0^2 B_0\) is well correlated with X-ray luminosity for both the Sun and other stars (Pevtsov et al. 2003; Reimers 2012), with a scaling law \(L_X \sim \Phi^{1.15}\). This results in

\[
\frac{\Phi_{\text{high}}}{\Phi_{\text{low}}} = \left( \frac{L_X}{L_{X,\odot}} \right)^{0.87} \left( \frac{R_0}{R_{\odot}} \right)^n ,
\]

(22)

where we have assumed the same global magnetic field topology \((n)\) for the Sun and the star, as well as the same height \(r\) where \(\Phi_{\text{high}}\) is evaluated. In case of a Sun-like star \((R_0 = R_{\odot})\), the overlying field would increase as \(L_X^{0.87}\) in this simple model. Therefore, it would be about a factor of \(10^3\) stronger for a star with \(L_X = 10^{30}\) erg s\(^{-1}\) if adopting \(L_{X,\odot} = 10^{26.5}\) erg s\(^{-1}\). We further assume that the critical flare energy is related to the lower coronal magnetic flux, which is dominated by the properties of the source region (Wang & Zhang 2007). The radiated energy in a flare is typically a fraction \(f = 0.1\) of the free magnetic energy \(E_{\text{mag}} = B_{\text{AR}}^2 L^3/(8\pi) = \Phi_{\text{AR}}^2/(8\pi L)\) (e.g. Shibata et al. 2013), where \(B_{\text{AR}}\) is the magnetic field strength of the AR, \(L\) its length scale, and \(\Phi_{\text{AR}}\) the magnetic flux of the AR. If we estimate \(E_{\text{crit}}/E_{\text{crit},\odot} = E_{\text{mag},\star}/E_{\text{mag},\odot}\)
This would result in a shallower increase of the critical flare dissipated energy in solar flares scales as
\[ \Phi_{\text{crit, }}^2 (\Phi_{\text{AR, }})^2, \tag{23} \]
if assuming similar length scales \( L \). Finally, using \( \Phi_{\text{AR, }}/\Phi_{\text{AR, } } \) as a proxy for \( \Phi_{\text{low, }}/\Phi_{\text{low, } } \) results in
\[ \frac{E_{\text{crit, }}}{E_{\text{crit, }}} = \left( \frac{L_X}{L_{X, \odot}} \right)^{1.74} \left( \frac{R_*}{R_{\odot}} \right)^{2n}. \tag{24} \]
Thus, for a Sun-like star \((R_* = R_{\odot})\), the critical flare energy for an eruptive flare could be a factor \( 10^9 \) higher for an active star with \( L_X = 10^{30} \) erg \( s^{-1} \) compared to the Sun, indicating that only the most energetic superflares may be accompanied by CMEs on young solar-like stars. On the other hand, Aschwanden et al. (2014) found from observations that the dissipated energy in solar flares scales as \( E_{\text{flare}} \sim B R L^{3/2} \).

This would result in a shallower increase of the critical flare energy \( \sim (L_X)^{0.87} \), indicating that \( E_{\text{crit}} \) would be a factor of \( 10^3 \) higher for a star with \( L_X \approx 10^{30} \) erg \( s^{-1} \).

We calculate the CME occurrence and mass-loss rates from Eq. 9 and the simplified step function association rate derived here. In Fig. 8, we show the ratios of the respective rates using the scaled association to those obtained with assuming the solar value, for a scaling \( \sim L_X^{0.87} \). Note that it was necessary to increase \( M_{\text{max}} \), since for the simplified step function association rate, the critical CME mass corresponding to \( E_{\text{crit}} \) exceeded \( M_{\text{max}} \) for stars with low \( L_X \). However, if \( M_{\text{max}} \) is chosen sufficiently high to avoid this, the resulting ratios are not very sensitive to the exact choice of \( M_{\text{max}} \). One can see that the occurrence rates are affected more severely by a scaled association rate than the associated mass-loss. For large \( \alpha \), the occurrence rates can be suppressed by several orders of magnitude for the most active stars. For small \( \alpha \), they can be lower by factors of 10 to 100. This is similar to the suppression of the mass-loss rates for large \( \alpha \), whereas the mass-loss rates for small \( \alpha \) are barely affected. Note also that for stars less active than the Sun, the occurrence and mass-loss rates could be higher by factors of a few due to weaker confinement. Assuming the steeper scaling \( \sim L_X^{1.74} \) suppresses both rates by even larger factors for active stars.

Although the association rate scaling derived in this section is likely too crude to draw firm conclusions on this issue, the results indicate that this topic should be studied in more detail in the future. What is of importance is that the critical flare energy, which is in reality rather a typical flare energy above which mostly eruptive flares occur, could possibly become higher than the maximum flare energy which can be generated by a star. This could indicate that only the largest superflares are typically accompanied by CMEs, or even that CMEs are rare also in these cases. Note that in reality, active regions on young stars can be much larger than the solar ones, increasing \( \Phi_{\text{flare}} \), and thus flares may remain eruptive also for increased confinement. Moreover, due to possibly larger heights of stellar flare regions, the overlying field may be weaker than assumed here, but this depends also strongly on the dominating field topology. Additionally, the overlying field could still be dominated by the AR or neighboring ARs, so that the global field underestimates the local field strength. It is obvious that more detailed knowledge on AR parameters on active stars would be needed to address this problem realistically. However, the toy model indicates that ignoring the modified confinement conditions in active stars could lead to a significant overestimate of associated CMEs if simply assuming that all energetic flares on such stars are eruptive events. Further modeling of flux ropes within realistic stellar magnetic fields (e.g. Drake et al. 2016) could give important insights on this issue.

5 SUMMARY

We develop an empirical model relating stellar flare rates with solar flare–CME relationships to estimate the CME occurrence rates and associated mass-loss on active stars. The mass-loss rates found for the most active stars are higher than existing observations of their total mass-loss rates, indicating limits to the extrapolation to the youngest stars. By evaluating all ingredients entering our empirical model, we identify the solar flare–CME association rate as the most uncertain component. Despite their close relation to flares, CMEs may only occur under certain conditions of the overlying magnetic field. Although flare rates and their maximum energies increase with active region sizes and field strengths, as well as the star’s overall activity level, the global magnetic field may hinder eruptions. Since the flare–CME association rate is also dependent on coronal confinement, this is likely the main pitfall of models aiming to predict stellar CME rates simply from flare occurrences. More direct detections of CMEs on active stars, as well as better measurements of total stellar mass-loss rates, would be needed to infer better constraints on the CME rates. Moreover, progress in modeling active region magnetic fields on stars with different global magnetic field topologies and strengths could also provide important insights. We conclude that due to this issue the true CME occurrence rates of active stars, despite their strong flaring, still remain elusive.

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APPENDIX A: TABLE

This paper has been typeset from a TeX/LaTeX file prepared by the author.
Table A1. Stars with mass-loss measurements from Lyα absorption. Spectral types, X-ray luminosities and mass-loss rates are taken from Wood et al. (2005b, 2014). Flare rates ($E_X > 10^{32}$ erg) are calculated using the flare power law from Audard et al. (2000). CME mass-loss rates are calculated as described in section 2.7 for $\alpha = 1.8$, the values in brackets give the range $\alpha = 1.5–2.5$. The last column estimates the ratio of mass-loss rates from CMEs to those of winds (only given for $\alpha = 1.8$), assuming $M_{\text{wind}} = M_{\text{obs}} - M_{\text{CME}}$, for cases where $M_{\text{obs}} > M_{\text{CME}}$.

| star     | spectral type | log $L_X$ [erg s$^{-1}$] | flare rate [day$^{-1}$] | $M_{\text{CME}}$ [$M_\odot$] | $M_{\text{obs}}$ [$M_\odot$] | $M_{\text{CME}}/M_{\text{wind}}$ |
|----------|---------------|---------------------------|--------------------------|-------------------------------|-------------------------------|----------------------------------|
| Proxima Cen | M5.5V         | 27.22                     | 0.14                     | 0.081 (0.025–1.5)             | $<0.2$                        | $>0.68$                          |
| $\alpha$ Cen | G2V+K0V     | 27.70                     | 0.41                     | 0.3 (0.11–4.5)                | 2                             | 0.18                             |
| 61 Cyg A   | K1V           | 28.32                     | 1.6                      | 1.5 (0.74–18)                 | 30                            | 0.05                             |
| $\epsilon$ Ind | K5V         | 27.45                     | 0.24                     | 0.15 (0.052–2.6)              | 0.5                           | 0.43                             |
| 36 Oph     | K1V+K1V      | 27.39                     | 0.21                     | 0.13 (0.043–2.2)              | 0.5                           | 0.35                             |
| EV Lac     | M3.5V         | 28.34                     | 1.67                     | 1.6 (0.78–19)                 | 15                            | 0.12                             |
| 70 Oph     | K0V+K5V      | 28.99                     | 6.93                     | 7.9 (5.2–77)                  | 1                             | –                                |
| $\xi$ Boo A | G8V          | 28.86                     | 5.81                     | 5.8 (3.6–58)                  | 0.5$^a$                       | –                                |
| $\xi$ Boo B | K4V          | 27.97                     | 1.15                     | 0.61 (0.26–8.2)               | 4.5$^a$                       | 0.16                             |
| 61 Vir     | G5V           | 26.87                     | 0.067                    | 0.029 (0.0074–0.67)           | 0.3                           | 0.11                             |
| $\xi^1$ UMa | G1.5V        | 28.96                     | 6.49                     | 7.4 (4.7–72)                  | 0.5                           | –                                |

$^a$ Total system mass-loss rate is $5M_\odot$, this splitting is one of the possibilities discussed by Wood & Linsky (2010).