Solar and Stellar Coronal Mass Ejections
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Understanding Coronal Mass Ejections in Magnetically-Active Stars

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Abstract. While Coronal Mass Ejections (CMEs) are known to be the most energetic manifestation of magnetic activity on the Sun, their stellar counterparts have remained, for the most part, elusive to our detection attempts. This situation, which is in stark contrast with the significantly enhanced observed level of flaring activity of stars, questions our understanding of the extension of the solar flare-CME connection to the stellar domain. In this presentation, I have emphasized the crucial role played by the stellar magnetic field in shaping the properties of CMEs in active stars. With the aid of state-of-the-art numerical simulations, we have explored the process of magnetic confinement of CMEs by a strong large-scale stellar magnetic field. This exploration includes multiple consequences ranging from the existence of the eruption itself, to different observational signatures emerging as this process takes place in the stellar atmosphere. These results are placed in context with our current observational knowledge of stellar CMEs and avenues are given to continue improving our understanding of these transient events on other stars.

Keywords. Magnetohydrodynamics (MHD), stars: activity, stars: coronae, stars: flare, stars: winds, outflows, Sun: coronal mass ejections (CMEs), Sun: flares

1. Introduction

Flares and coronal mass ejections (CMEs) are the solar system's most energetic phenomena. Flares manifest as sudden radiation bursts emerging from the solar atmosphere across the electromagnetic spectrum, while CMEs entail a localized discharge of magnetized plasma into interplanetary space. Their generation typically involves a sequence of processes intricately linked to coronal magnetic field reorganization and reconnection (Chen 2011; Shibata & Magara 2011; Webb & Howard 2012; Benz 2017; Fan 2021). Recent studies have consistently shown that the most intense solar flares, particularly those classified as X-class in the GOES scale, are almost always accompanied by a CME (Andrews 2003; Yashiro & Gopalswamy 2009; Compagnino et al. 2017), and that CME mass and kinetic energy are positively correlated with the X-ray fluence of the flare (Lamy et al. 2019). Furthermore, it is now evident that CMEs carry a significantly larger portion of the available energy compared to X-ray/EUV flares (Emslie et al. 2005, 2012). Nonetheless, when accounting for thermal and non-thermal emissions across various wavelengths such as white light/UV continuum, the combined energies of flares and CMEs seem to be comparable (Kretzschmar et al. 2010; Kretzschmar 2011; Emslie et al. 2012; Aschwanden et al. 2017).

Continuous solar monitoring has spurred substantial advancements in the field, as has been clearly demonstrated by the talks during this conference. In contrast, observations suggest that the flare-CME relationship in stellar cases may deviate from its solar counterpart. Evidence of this comes in different forms. On one hand, the coronae of very

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active stars (particularly M-dwarfs) exhibit a seemingly perpetual flaring activity (see Kashyap et al. 2002, Huenemoerder et al. 2010; Kowalski 2024), often described by a superposition of flares in their light curves (e.g., Audard et al. 2000; Caramazza et al. 2007; Tristan et al. 2023). This heightened flare activity potentially implies a corresponding prevalence of stellar CMEs, a notion explored by various authors in the context of stellar evolution and environmental conditions surrounding stellar systems (e.g., Lammer et al. 2007; Khodachenko 2007; Cohen et al. 2011; Aarnio et al. 2012; Drake 2013; Schnepf et al. 2015; Takahashi et al. 2016; Cranmer 2017, Kay et al. 2019; Cherenkov et al. 2017). Notably, flares in highly active stars can be orders of magnitude more energetic than solar flares and occur with much greater frequency (e.g., Osten et al. 2007; Kowalski et al. 2010; Shibayama et al. 2013; Osten 2016; Davenport et al. 2019; Kowalski 2024).

On the other hand, as extensively discussed by Drake 2013, extrapolating the solar flare-CME relationships to active stars leads to problematic outcomes. One significant issue is the prediction of a substantial contribution from CMEs to the stellar mass loss rate ($\dot{M}$), resulting in $\dot{M}$ values that are up to four orders of magnitude higher than the accepted solar value (attributed to the solar wind) and approximately two orders of magnitude above the highest $\dot{M}$ estimate derived from astrospheric Lyman-α absorption (Wood et al. 2002, 2005, 2014, 2021). (Osten & Wolk 2015) achieved comparably large $\dot{M}$ predictions by extending flare-CME relationships to cover the various energy bandpasses and flare frequencies observed in solar-type and low-mass stars. Cranmer (2017), using a slightly different method, considered a solar-based relationship between surface-averaged magnetic fluxes and the contribution of CMEs to the total stellar mass loss. According to this model, CMEs would significantly dominate the mass loss budget in young stars (a few Myr old), by factors of 10 to 100, surpassing the contribution from the steady stellar wind even in later stages (younger than 1 Gyr). Odert (2017) introduced an empirical model (also incorporating solar extrapolations), which shows relatively good agreement on the $\dot{M}$ for moderately active stars (i.e., surface X-ray fluxes $F_X < 10^6$ erg cm^{-2} s^{-1}), but still predicts large values at the high-activity end. Still, all of these approaches would eventually lead to CME-driven mass loss rates that are too large to be reconciled with the required radio transparency of the wind (see the discussion in Lim & White 1996). Note also that the recent study of Kislyakova et al. (2024) reports relatively small mass loss rate values for 3 cool stellar systems (2 binaries, one single star) using an independent methodology based on the stellar wind-ISM charge-exchange X-ray signature. As such, it must be concluded that our current knowledge on stellar winds from cool main-sequence stars does not support the expectation of high contributions from stellar CMEs based on solar extrapolations.

Drake (2013) also pointed out that maintaining solar-like flare-driven CME activity would require implausibly high energy requirements, reaching up to ten percent of the stellar bolometric luminosity for active stars in the saturated regime. They concluded that either the relationships between CME mass/speed and flare energy must flatten for X-ray energies $\gtrsim 10^{31}$ erg, or the flare-CME association rate must significantly decrease below 1 for more energetic events (contrary to the solar case).

To exacerbate these issues and contrary to the "high CME activity expectation", solid evidence for stellar CMEs remains scarce and challenging to obtain. A few studies have noted blue-wing enhancements in the Balmer lines of M dwarfs, interpreted as eruptive stellar filaments (e.g., Houdebine et al. 1990; Gunn et al. 1994; Vida et al. 2016). Guenther & Emerson (1997) identified a distinct Hα blue-wing enhancement in the spectrum of the weak T Tauri star DZ Cha (RX J1149.8–7850), attributing it to a CME and inferring an ejected mass in the range of 10^{18} – 10^{19} g (larger than the most massive solar CMEs). By characterizing the column density absorption profile evolution after a large

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flare on Algol, Moschou et al. (2017) deduced an even larger ejected mass in the range of 10^{21} – 10^{22} g (see also Favata & Schmitt 1999). Still, several additional attempts to detect stellar CMEs using radio and optical data have yielded no significant signatures, even in dedicated observations (e.g., Leitzinger et al. 2014; Crosley et al. 2016; Villadsen 2017; Crosley and Osten 2018, Muheki et al. 2020a, 2020b).

In a recent development, Veronig (2021) documented a series of 21 coronal dimmings across 13 active late-type stars, interpreting them as indirect signatures of CMEs. The phenomenon of coronal dimmings associated with CMEs has been a consistent observation on the Sun for over two decades, particularly at EUV and soft X-ray wavelengths (Hudson et al. 1996; Sterling & Hudson 1997; Zarro et al. 1999). These dimmings are observable across various coronal temperatures but are most conspicuous in the $1-2$ million Kelvin plasma of the quiet corona (Vanninathan et al. 2018; Dissauer et al. 2018). They typically manifest at the bipolar ends of closed magnetic field lines, which become stretched or temporarily opened during an eruption, resulting in the depletion of coronal plasma due to expansion and mass loss caused by the CME (Thompson et al. 1998; Harra et al. 2016). While the X-ray dimming signatures reported by Veronig (2021) dramatically exceeded the nominal values observed on the Sun (by more than one order of magnitude), this study did not provide estimates for the physical properties of these potentially extreme events. Based on the same dimming phenomenology, Loyd et al. (2022) recently derived a upper limits of mass and kinetic energy of a few 10^{15} g and 10^{31} erg respectively for a candidate CME event observed after a flare in the K2V star ϵ Eridani.

To date, the most compelling stellar CME candidates come from the research conducted by Argiroffi et al. (2019) and Namekata et al. (2021). In the former, blue-shifted cool coronal emission following a flare on the giant star HR 9024 (G1III) was reported. The estimated properties for this event ($M_{\rm CME} \sim 10^{21}$ g, $K_{\rm CME} \sim 10^{34}$ erg) surpass the typical parameter space observed in solar eruptions. In this case, the CME developed under magnetic and coronal conditions comparable to those expected for active Sun-like stars (Borisova et al. 2016) but it was hosted by a star with significantly reduced surface gravity. In the latter study, a blue-shifted hydrogen absorption component with a high velocity of -510 km/s was observed shortly after a large flare on the young Sun-like star EK Dra (G5V). The temporal changes in the spectra closely resembled those of solar filament eruptions, strongly suggesting a stellar CME event. The erupted filament mass of $\sim 10^{18}$ g was notably larger than those of the largest solar coronal mass ejections.

In a prior study, Moschou (2019) reexamined the most promising stellar flare-CME candidates documented in the literature, obtaining constraints on CME parameters such as mass and kinetic energy (see Fig. 1). Their investigation encompassed events identified through sustained X-ray absorption subsequent to a stellar flare (e.g., Favata & Schmitt 1999; Moschou et al. 2017), as well as potential candidates inferred from post-flare Doppler-shift signatures observed in optical or UV spectral lines (e.g., Houdebine et al. 1990; Leitzinger et al. 2011). The compilation presented by Moschou (2019) offered crucial insights into the behavior of the flare-CME relationship within the stellar context: While the estimated masses of the CMEs generally aligned with a solar extrapolation based on the observed X-ray energy of the flares, the kinetic energy associated with each eruption fell notably below expectations. As depicted in Fig. 1, the characteristics of the CME events deduced by Argiroffi et al. (2019) and Namekata et al. (2021) likewise adhere to this overarching trend.

2. Suppression of CMEs: The role of the large-scale magnetic field

One mechanism that may decrease the association between solar flares and CMEs in active stars, thus circumventing the energy/mass loss issues highlighted by Drake

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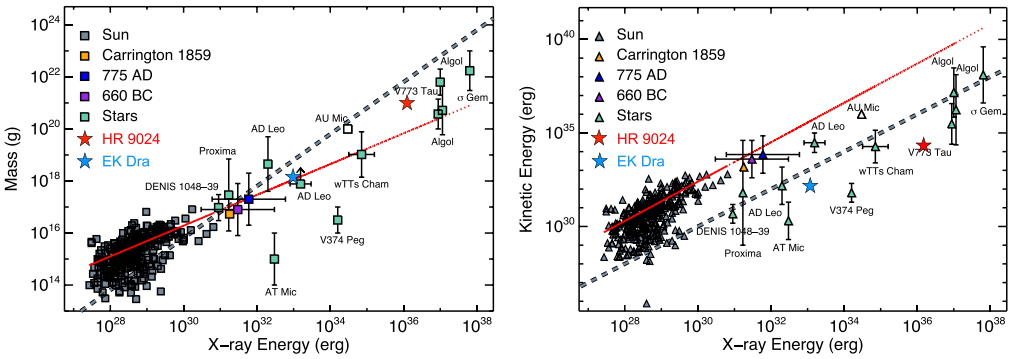


Figure 1. Current observational constraints on the flare-CME connection in cool stars. Derived CME masses (left) and kinetic energies (right) are plotted against the X-ray radiated energy of the associated flare. Recent (gray) and historical (yellow, blue, purple) solar events are shown alongside stellar candidate eruptions (green). The star symbols correspond to the individual events currently regarded as stellar CME detections, observed in the stars HR 9024 (G1III, red) and EK Dra (G1.5V, cyan). Red lines represent fits and extrapolations of the solar data. Gray dashed lines indicate a constant ratio of CME mass to flare X-ray energy (left) and parity between flare X-ray and CME kinetic energies (right). Note that while the stellar CME masses appear roughly aligned with the solar extrapolation, the kinetic energy of those events is significantly lower than the expectation (by several orders of magnitude). **Adapted from:** Moschou (2019), Argiroffi et al. (2019) and Namekata et al. (2021).

(2013), involves the suppression of plasma ejection by a robust overlying magnetic field (Drake et al. 2016, also discussed by Odert 2017). This theory has been proposed to elucidate the behavior of specific active regions on the Sun that are rich in flares but devoid of CMEs (e.g., Thalmann et al. 2015, 2017; Sun et al. 2015; Liu et al. 2016). In the stellar regime, spectropolarimetry and Zeeman-Doppler Imaging (ZDI) have uncovered the widespread presence of magnetic fields in cool main-sequence stars (Donati & Landstreet 2009; Reiners 2012; Kochukhov 2021). ZDI, which is sensitive to large-scale magnetic components, reveals that active stars possess surface field strengths significantly greater than those on the Sun (e.g., Morgenthaler et al. 2012; Jeffers et al. 2017; See et al. 2019). These variations correspond to photospheric large-scale magnetic fields ranging from 10 G to several 10^2 G in young Sun-like stars (e.g., Alvarado-Gómez et al. 2015; Hussain et al. 2016; Folsom et al. 2016, 2018), and reaching up to a few 10^3 G in M-dwarfs (e.g., Morin et al. 2008; Morin et al. 2010; Lavail et al. 2018). Similar average unsigned magnetic field strengths have also been reported from Zeeman Broadening/Intensification techniques applied to Sun-like stars (Kochukhov et al. 2020) and M-dwarfs (Reiners et al. 2022).

The concept of magnetic suppression of stellar CMEs was briefly explored in a magnetohydrodynamic (MHD) simulation by Drake et al. (2016), where a large solar CME failed to erupt when subjected to the large-scale magnetic field configuration akin to that of a much more active star (AB Doradus; Hussain et al. 2002). Our recent work, which integrates information on stellar magnetism with numerical simulations, has been pivotal in understanding the disparity between flare and CME occurrence in stars and interpreting the limited available data. Employing realistic 3D MHD models, we demonstrated that the stellar large-scale magnetic field can create a suppression threshold that prevents CMEs of certain energies from escaping (Fig. 2; see also Alvarado-Gómez 2018; Alvarado-Gómez et al. 2022). Our analysis also showed that the overlying magnetic field significantly reduces the overall speeds of CMEs (and consequently their associated kinetic energies), which contrasts with extrapolations from solar data. Conversely, the

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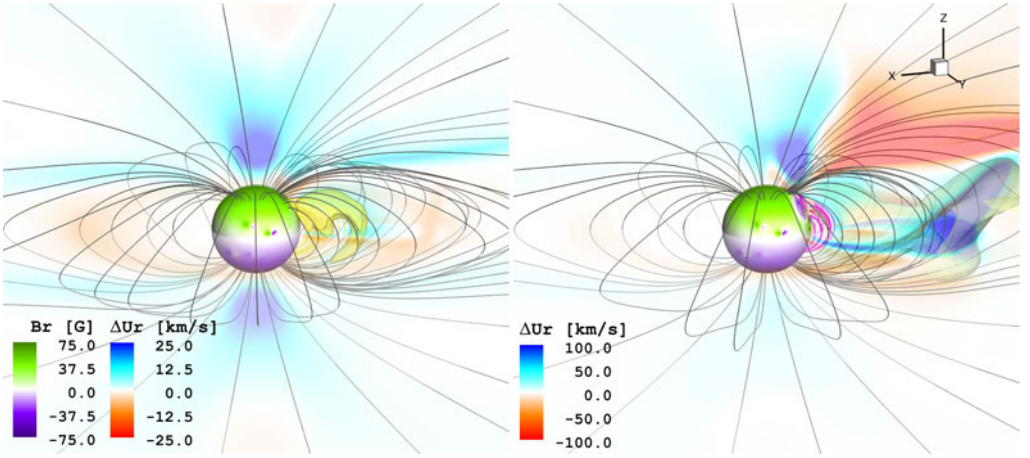


Figure 2. Examples of a confined (left) and escaping (right) CME evolving within a solar magnetic field configuration modified to host a stronger large-scale dipolar field (75 G). The escaping CME is driven by a flux-rope eruption containing $\sim$15 times more magnetic energy compared to the confined case. The central sphere represents the stellar surface, colored by the magnetic field that drives the model. A secondary color scale indicates a proxy (ΔUr) for the coronal Doppler shift velocity relative to pre-CME conditions. The detected eruption is shown as a translucent yellow iso-surface ($\times$3 density enhancement). Selected magnetic field lines related to the large-scale field (gray) and surrounding the eruptive active region (magenta) are shown. The field of view in both panels spans 12 $R_\star$. **Adapted from:** Alvarado-Gómez (2018).

total mass perturbed in the simulated events approximately followed the solar flare-CME relationship extended to the stellar context. Notably, these two predictions are consistent with the properties of the stellar CME candidates observed to date (see Fig. 1).

3. Exploring the stellar CME confinement and its observational signatures: The case of M-dwarf stars

As previously noted, M-dwarfs are characterized by frequent and energetic flaring (e.g., Howard et al. 2018; Günther et al. 2020), persisting even at relatively old ages in their evolutionary stages (France et al. 2020), and occurring even when they appear "quiet" in optical data (Loyd et al. 2020). Their surface magnetic fields, reaching up to a few kG, are the strongest observed among cool main-sequence stars (Reiners 2012; Kochukhov 2021). Importantly, these stars are primary targets for the atmospheric characterization of many current and future exoplanet missions. Due to their lower luminosity, the habitable zone —where an exoplanet could maintain surface liquid water— is situated very close to the star, sometimes up to ten or more times closer than the distance between the Sun and Earth (Kopparapu et al. 2014; Shields et al. 2016). These close-in orbits have short periods, ranging from a few days to a couple of weeks, which facilitates the detection and follow-up of these systems.

Numerous factors then underscore the importance of numerically investigating CMEs in M-dwarfs, including their potential confinement, which holds significant relevance for both stellar and exoplanetary studies. Such simulations can offer valuable insights and constraints for ongoing and future observational efforts targeting these energetic phenomena. In our work (Alvarado-Gómez et al. 2019, 2020), we conducted the first realistic modelling of CME events in M dwarf stars. Our findings revealed marked disparities in how the corona and stellar wind respond to these eruptions under magnetic confinement, contrasting with their solar counterparts (see Fig. 3). Depending on the CME's energy

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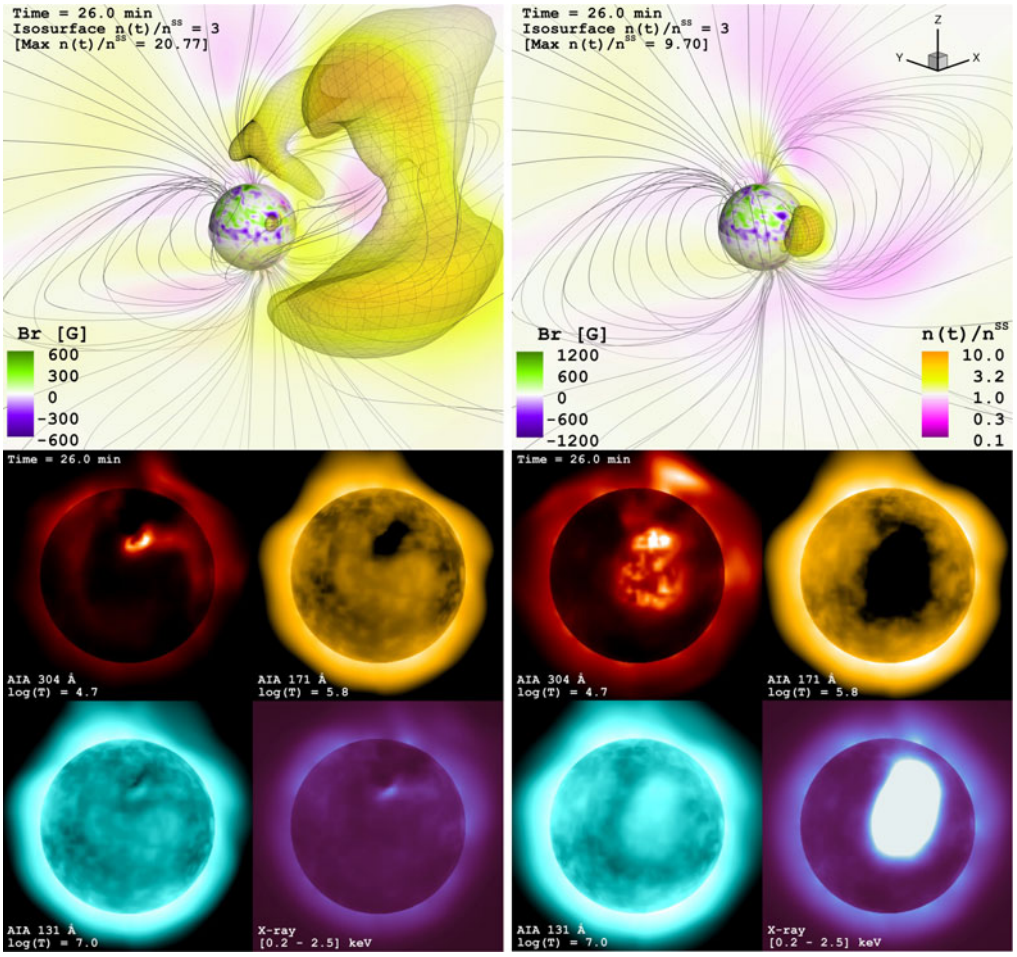


Figure 3. Snapshots from two time-dependent numerical simulations comparing the corona and stellar wind response during escaping (left) and confined (right) CME events on the flare-star Proxima Centauri (M5.5V, 4.85 Gyr). The geometry of the magnetic field driving the models is provided by the 3D dynamo simulation performed by Yadav et al. (2016). Each case employs a different scaling (*Left:* $B_{\rm r}^{\rm max} = \pm 600$ G, *Right:* $B_{\rm r}^{\rm max} = \pm 1200$ G) adjusted to reach the values observed in low- and moderately-active M dwarfs (Reiners et al. 2022). While an identical CME is initiated in both cases ($M_{\rm CME} = 4 \times 10^{17}$ g, $E_{\rm CME}^{\rm K} = 10^{35}$ erg), the eruption is only able to escape in the weaker magnetic field configuration, as indicated by the density ratio visualizations in the top row. Naturally, the coronal response is completely different in both cases, as can be seen from the simulated full-disk images in the bottom panels, synthesized in X-ray and EUV wavelengths (observer towards the $-y$ axis). **Adapted from:** Alvarado-Gómez et al. (2019).

and the characteristics of the stellar magnetic field (i.e. the confinement properties), notable signatures include:

- In CME events with weak suppression, a sudden increase –by factors ranging from approximately 5 to more than 10– in integrated X-ray coronal emissions (0.2 – 2.5 keV), lasting from tens of minutes to an hour is obtained. These brightenings resemble typical stellar flare events but are fueled not by magnetic reconnection but by rapid compression of coronal material.

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- The evolution of these flare-like transients show a swift evolution –under one hour– of Doppler shift signals (from red to blue), with velocities reaching up to 200 km s^{-1}, transitioning from hotter ($\log(T) \gtrsim 6.8$) to cooler ($\log(T) \lesssim 6.0$) coronal lines. Slower velocities (< 100 km s^{-1}) and longer durations (> 1 h) are anticipated for more strongly suppressed eruptions (either due to stronger stellar fields or weaker eruptions).
- Fully confined CME events would lead to a gradual enhancement of soft X-ray coronal brightness (by factors of approximately 2-3) over several hours. This emission would exhibit redshifts (< -50 km s^{-1}), indicative of in-falling material (referred to as coronal rain clouds).
- In all the simulated events (weakly and strongly suppressed) a decrease in the emission at mid-coronal temperatures is obtained. These decreases in emission resemble coronal dimming events on the Sun which display a very high association rate with CMEs (Harra et al. 2016; Dissauer et al. 2018). However, in our simulations, these also occur during fully confined eruptions where the material might be removed from the eruption site but launched to higher latitudes to fall back onto the star (so that no mass is ejected at the end). We also noticed important changes in thermodynamic structure of the corona due to plasma motions and compression which might also contribute to the reduction of flux at a particular temperature without the removal of coronal mass.
- In radio wavelengths, Type II bursts signal the presence of an MHD shock in the corona or inner heliosphere and are strongly linked to CMEs and Solar Energetic Particle events (SEPs). These shocks and their associated particle acceleration occur close to the solar surface (see Gopalswamy et al. 2009; Zucca et al. 2014). The frequency of a Type II radio burst is proportional to the ambient density ($\propto \sqrt{n}$), and their frequency drift can reveal properties of the shock. However, as noted in Sect. 2 and demonstrated in Alvarado-Gómez et al. (2020), due to magnetic suppression stellar CMEs are significantly slowed down becoming super-Alfvénic (and thus inducing shocks) much farther from the star. This effect is heightened in more active stars, which have higher Alfvén speeds in their corona due to stronger surface magnetic fields, creating less favorable conditions for shocks near the star (Villadsen and Hallinan 2019). Consequently, the associated Type II radio bursts occur at much lower frequencies, often near or below the ionospheric cutoff at 10 MHz. Therefore, the magnetic suppression of stellar CMEs significantly impedes their detection via Type II radio bursts from the ground.

4. Concluding Remarks

The stellar eruptive behavior, crucial for high-energy stellar astrophysics and exoplanetary science, remains largely unexplored beyond the Sun. While solar CME knowledge offers a fundamental basis, blindly applying its paradigm to other stars poses theoretical and observational challenges, especially concerning more active stars. Detailed numerical simulations are essential to study and characterize these energetic phenomena in cool stars under these constraints.

Our numerical experiments underscore the pivotal role of stellar magnetic fields in shaping CME properties. Advanced models of CME propagation in active stars demonstrate that these events can be partially or completely suppressed by the star's large-scale magnetic field. This magnetic suppression mechanism effectively reduces the flare-CME association rate as well as lowers the CME speed and kinetic energy, aligning with limited observational data. This process significantly affects expected CME signatures across different wavelengths, potentially limiting detection following solar analogies, such as Type II radio bursts.

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This suppression mechanism extends to stronger and more complex magnetic field regimes, such as those found in M-dwarfs. Contrary to what might appear at first glance, simulations indicate both escaping and suppressed CME events could pose significant risks to exoplanets. Direct impacts on exoplanet atmospheres and ionizing radiation from associated coronal responses (like compression flaring and up-flows/down-flows) may be detectable by upcoming high-energy astrophysics instruments.

Finally, understanding CMEs and associated phenomena in exoplanetary atmospheric studies requires realistic stellar-specific CME assessments, avoiding direct solar extrapolations. Accurate characterization of stellar CME properties and occurrence rates demands integrated multi-wavelength observations and sophisticated numerical modeling approaches.

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Questions/Discussion

A. Veronig: You demonstrated in your simulations that failed CMEs may form strong density enhancements due to compression which may produce flare-like light curves. Are the temperatures that can be achieved by this process similarly high as in flares?

J. D. Alvarado-Gómez: According to our models yes, some of the temperatures can be very high. Perhaps they will not reach the highest temperatures seen in stellar flares but definitely they reach X-ray and EUV emitting temperatures (so a few MK). Note that we do see these 'flare-like' signatures in all cases: when the CME escapes and when it is confined. The degree of confinement affects their duration (the less confined ones generate shorter, more impulsive 'flare-like' profiles whereas for more confined events the induced emission will last a bit longer, evolving in a more gradual way). While we have not estimated properly their energies, to a first order, the profiles emerging from fully-confined CME events will radiate more energy in XUV wavelengths compared to the ones generated for escaping CMEs.

K. Dissauer: From an observational point of view, what do you think would be required to confirm magnetic confinement?

J. D. Alvarado-Gómez: Interesting question. I believe that there are multiple observational hints already that magnetic confinement is taking place for the stellar regime. As I indicated in my talk, the fact that our searches for stellar CMEs have returned empty handed, contrary to our expectations based on solar behaviour, is probably one of them. In addition, as nicely presented by Tom Ayres in his 2015 paper on EK Dra (Ayres 2015), HST observations of this star reveal the persistent presence of 'downflows' visible in transition region/chromospheric lines. This behaviour is consistent with the picture of material trying to get ejected after reconnection events (i.e. flares) but not managing to escape and falling back onto the star. This chain of events is also very similar to what we obtain with our numerical models of suppressed CME events. While these observations might not completely 'confirm' the magnetic confinement of CMEs, they strongly support this scenario for active stars.

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