Solar and Stellar Coronal Mass Ejections
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All talk and no action: CMEs and prominences on M dwarfs

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Abstract. One of the most important questions in the field of exoplanets is the impact that stellar CMEs (and their energetic particles) may have on exoplanetary atmospheres. This is of particular importance if the parent star is an M dwarf, since their powerful flares suggest (based on the solar analogy) that they will have commensurably powerful CMEs. Stellar CMEs have proved difficult to detect however, leading to the suggestion that the solar relationship between flares and CMEs does not extend down to the M dwarf regime. Two lines of evidence - both modelling of coronal evolution in response to flux emergence and surface transport and observations of the surface magnetic energy and helicity densities - point to the low surface differential rotation of M dwarfs as a possible culprit.

Keywords. stars: activity, stars: coronae, stars: magnetic fields

1. Introduction

M dwarfs have been popular targets for exoplanet searches for some time. Not only are they very numerous, but their low mass and luminosity make them good candidates for detection methods searching for exoplanets in the star's habitable zone, where exoplanets can sustain bodies of liquid water on their surfaces. The atmospheres of these planets are, however, particularly at risk from the damaging effects of energetic particles accelerated by stellar coronal mass ejections or CMEs (Airapetian 2020). The reason for this is straightforward - a star with a low mass is cool and so has a habitable zone that is close to the star. Exoplanets at these orbital radii therefore have high orbital frequencies. As a result, an exoplanet in the habitable zone would be continuously impacted by CMEs if the parent star had a rate of coronal mass ejections of only six times that of the present-day Sun at maximum (Khodachenko 2007).

When this calculation was first published, this seemed to be a very achievable rate, since M dwarfs produce frequent and powerful flares (Kowalski 2024). It was expected that a correspondingly high rate of CMEs would be detected. In the intervening years, however, clear detections of stellar CMEs have proved remarkably elusive, although there is growing evidence of prominence eruption (Drake 2013; Notsu 2013; Odert 2017; Moschou 2019; Leitzinger 2020; Maehara 2021; Kanodia 2022; Wu 2022; Namizaki 2023; Inoue 2023; see also Veronig 2021). It is not clear whether this represents some characteristic of the ejection process that makes it difficult to detect with current methods, or whether it represents an underlying low rate of ejection.

2. Coronal dynamics

In order to understand the processes that drive coronal dynamics we need to consider both the rate at which magnetic flux emerges through stellar surfaces, and the various surface processes that subsequently act on that flux, transporting it in meridional flows,

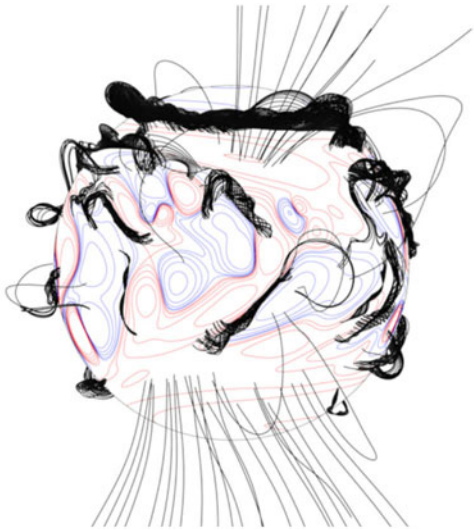

Figure 1. Twisted flux tubes formed in a stellar corona (taken from Gibb et al. 2016). Red and blue contours denote positive and negative surface magnetic field, respectively, and the black lines are field lines.

stretching and stressing it through surface differential rotation and causing it to diffuse. On the Sun, the fastest of these processes is the surface differential rotation. This has been measured for other stars (Marsden 2005; Marsden 2006; Barnes 2005; Reiners 2006; Jeffers 2011) where it is found to decrease with stellar mass, such that the lowest mass stars rotate almost as solid bodies. In order to assess the impact on coronal dynamics of this variation in shearing rates, Gibb (2014) undertook a pilot study considering the eruption and subsequent evolution of a single isolated flux tube. They found that the timescales for the formation and eruption of a twisted flux tube (the precursor of a CME) could be expressed as

$$\tau_{\text{formation}} \propto \sqrt{\tau_{\text{lap}} \tau_{\text{diffusion}}} \tag{1}$$

and

$$\tau_{\text{erupt}} \propto \tau_{\text{lap}}, \tag{2}$$

where $\tau_{\text{formation}}$ is the time to form a twisted flux tube, τ_{lap} is the time for the equator to advance one full rotation ahead of the pole and $\tau_{\text{diffusion}}$ is the diffusion timescale. Consequently, the lowest-mass stars, which have the largest values of τ_{lap}, have the longest timescales for the formation and eruption of these CME precursors. It seems that in the corona of an M dwarf, everything may just happen very slowly.

A subsequent full-star, long-term evolution study (see for example Fig. 1) considering a range of flux emergence and differential rotation rates, confirmed these trends (Gibb et al. 2016), but revealed a more complex interplay between the effects of flux emergence and differential rotation. The free magnetic energy (the maximum available for release) was found to depend principally on the flux emergence rate and hence ultimately on the stellar rotation rate. Changes in the differential rotation had little impact. This might suggest that M dwarfs which have high magnetic flux densities (and hence most likely high magnetic flux emergence rates) might be able to power frequent and powerful flares, even if they had little differential rotation. In contrast, the timescales for the formation and eruption of twisted flux tubes depended most sensitively on the differential rotation,

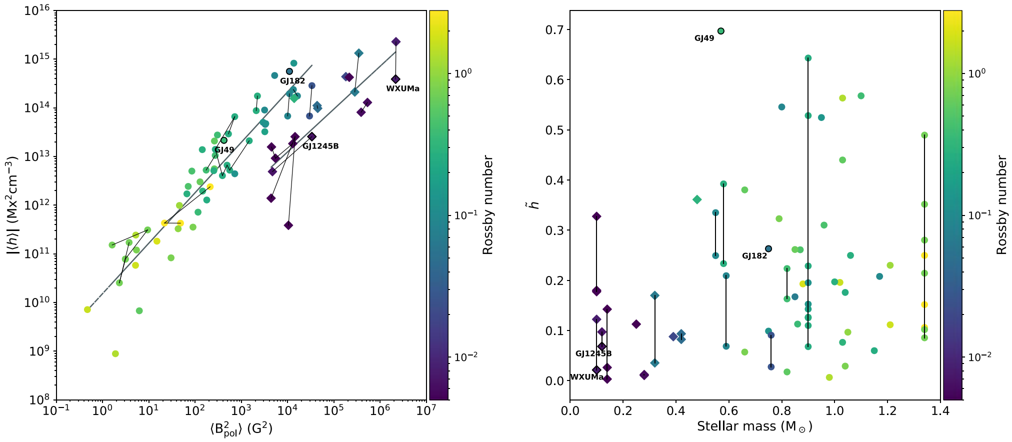

Figure 2. (Left) Absolute helicity density h for spherical harmonic degree $l \leq 4$ averaged across a single hemisphere versus the mean squared poloidal magnetic flux densities across the star. Diamonds represent stars with $M_\star < 0.5$ M$_\odot$. The dashed lines show the best fit of $|\langle h \rangle| \propto \langle B^2 \rangle^\alpha$. Best fit lines of stars with $M_\star < 0.5$M$_\odot$ and $M_\star > 0.5$M$_\odot$ are shown separately, resulting in $\alpha = 0.77 \pm 0.18$ and $\alpha = 1.11 \pm 0.07$ respectively. (Right) The efficiency of the production of helicity density h ($l \leq 4$), defined as $\tilde{h} \equiv |\langle h \rangle| / \langle R_\star B^2 \rangle$, versus stellar mass.

although high flux emergence rates could shorten these timescales. Thus the rate of CME eruption might be expected to vary more with differential rotation (and hence stellar mass) than flaring rates.

3. Mapping magnetic twist at stellar surfaces

It appears from the Gibb et al. (2016) study that in stellar coronae the two processes of flaring and eruption might show different trends with surface differential rotation. One way to test this would be to map the surface distribution of magnetic twist in stars with a range of rotation rates and masses (and hence surface differential rotation). This has already been done - although only for the large-scale field - using the spectropolarimetric technique of Zeeman-Doppler Imaging (Lund 2020). These authors mapped the large-scale surface "mean twist" or magnetic helicity density across the surfaces of over 100 stars. They found that the lowest mass stars, which lack a radiative core and therefore cannot power an interface dynamo, showed a relationship between the poloidal magnetic energy and mean twist that was different to that of stars that had a solar-like internal structure, with a convective outer zone and a radiative core (Fig. 2). At the same value of the poloidal magnetic energy, the lowest mass stars had significantly lower mean twist, since much of their (strong) poloidal fields did not link through the surface toroidal fields (Lund 2021). This can be seen in the ratio of the helicity density to the energy density, which is a measure of the efficiency with which stars can produce twist (Fig. 2). While stars of mass $M_\star > 0.5M_\odot$ have efficiencies approaching 1, the lower mass stars, with masses $M_\star < 0.5M_\odot$, have much lower values. This suggests that while they can generate very strong fields, the structure of these fields ensures that they do not have correspondingly large helicity densities.

4. Discussion

Both the observational and theoretical studies described above point to the fundamental difference between the magnetic fields produced by fully convective stars and those of stars like the Sun that have a tachocline and so can support an interface dynamo.

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This difference is also seen in the structure of the magnetic fields of pre-main sequence stars, before and after the growth of the radiative core (Folsom 2016; Gregory 2016). The apparent lack of CME eruptions that are as numerous as the flares seen on M dwarfs may of course be due to the confinement of CMEs by the strong, large-scale fields of M dwarfs (Alvarado-Gómez 2018). The lack of surface shearing in the lowest-mass stars, however, may also simply reduce the rate at which CMEs are produced to the point where they become difficult to detect. Low mass stars may have much higher rates of magnetic flux emergence than the Sun - and so be able to power large and frequent flares - but their low rates of surface shear may make eruptive process less common than the solar analogy might suggest.

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