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Where are the stellar coronal mass ejections?

Krisztián Vida[1,2], Martin Leitzinger[3], Petra Odert[3], Levente Kriskovics[1,2], Anna Görgei[1,2,4], Heidi Korhonen[5], Zsolt Kővári[1,2], Katalin Oláh[1,2] and Bálint Seli[1,2,4]

[1]Konkoly Observatory, Research Centre for Astronomy and Earth Sciences, (Eötvös Loránd Research Network (ELKH)), H-1121 Budapest, Konkoly Thege Miklós str 15-17, Hungary
email: vidakris@konkoly.hu

[2]CSFK, MTA Centre of Excellence, Budapest, Konkoly Thege Miklós str 15-17, H-1121, Hungary

[3]Institute of Physics/IGAM, University of Graz, Universitätsplatz 3, A-8010 Graz, Austria

[4]Eötvös University, Department of Astronomy, Pf. 32, 1518, Budapest, Hungary

[5]European Southern Observatory (ESO), Alonso de Córdova 3107, Vitacura, Santiago, Chile

Abstract. Flares and coronal mass ejections (CMEs) can have serious effects on their surroundings: they can erode or completely destroy atmospheres of orbiting planets over time and also have high importance in stellar evolution. We present a search in archive spectra of dwarf stars from solar-like objects to M-dwarfs aimed to find a large number of stellar CMEs suitable for statistical analysis. For M-dwarfs, we found event rates that are lower than we could expect from the solar paradigm, and no convincing events for solar-like stars. What can be behind this low number of events? How can we possibly find more events?

Keywords. techniques: spectroscopic; Sun: coronal mass ejections (CMEs); stars: activity; stars: late-type; stars: magnetic fields; stars: flare

1. Introduction

Flares and related processes affect both the evolution of stars and their surrounding exoplanets: their impact raises serious questions on potential habitability, even if the planet is in the habitable zone. Numerous energetic events – such as flares and coronal mass ejections (CMEs) – could erode the atmospheres of the planets located close to their host stars and render them uninhabitable (Khodachenko et al. 2007; Yelle et al. 2008). Flares and CMEs can be relatively easily observed on our Sun, as it is monitored by many ground based and space-borne instruments with high spatial and temporal resolution. In fact, most of the larger solar flares are accompanied by CMEs. All these phenomena are a part of solar activity, and we can directly observe their impacts on Earth and other Solar System planets in the form of aurorae or geomagnetic storms. While these phenomena can be easily seen on the Sun, they are more relevant and more energetic on cooler stars, where they can reach much larger scales. Stellar activity is one of the most important aspects of planetary habitability, and the only one that we can currently study directly lacking the ability of detailed observations of exoplanet properties.

While stellar flares are relatively easy to detect in light curves due to their typical light curve shape, CMEs are much harder to spot. Currently there are few candidates in shorter wavelengths (Leitzinger et al. 2011; Argiroffi et al. 2019; Chen et al. 2022). Only recently, Veronig et al. (2021) presented more than 20 stellar CME candidates

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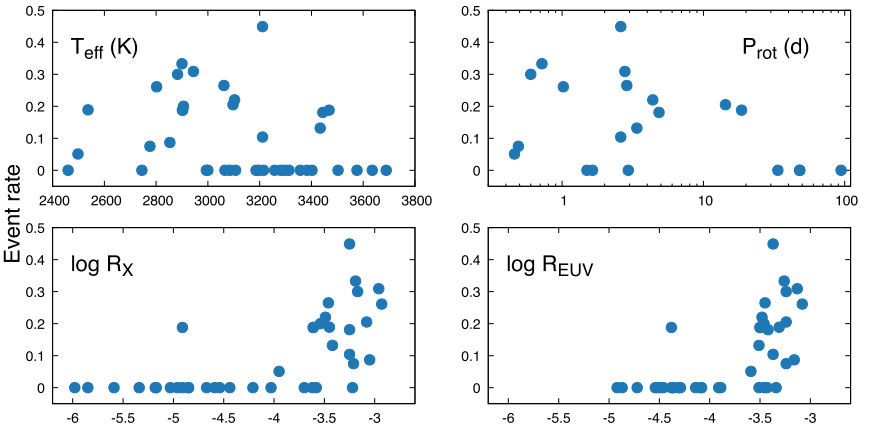


Figure 1. Stellar CME rate on late-type stars as a function of some of the physical parameters of the host star. We found that the CME rate was higher on later type fast-rotating stars with higher magnetic activity. For details, see Vida et al. (2019).

determined from coronal dimmings in EUV and X-ray data. Moreover, there have been a handful of studies reporting on the detection of hydrogen column density variability during flaring, interpreted as self-similar expanding plasma moving away from the star (see Moschou et al. 2019 for a review) resembling CMEs and/or erupting prominences. The efforts to find CME signatures in radio have proven yet mostly unfruitful (see Villadsen 2017, and references therein) with one radio burst that might be related to a CME (Zic et al. 2020) – most of the detection were based on the asymmetric distortion of the Balmer lines (mostly the Hα region) due to the Doppler-shifted signature of the ejected plasma (e.g., Houdebine, et al. 1990; Gunn et al. 1994).

2. Targeted searches for coronal mass ejections

For a long time, signatures of stellar CMEs were serendipitous single detections only, dedicated CME search projects started only in the last decade. Unfortunately stellar CMEs are impossible to forecast, therefore their detection needs long observing campaigns with at least mid-sized telescopes equipped for mid/high-resolution spectroscopy (Muheki et al. 2020; Namekata et al. 2021). Few-night observing runs targeting open clusters with several promising targets at the same time were yet unsuccessful (Leitzinger et al. 2014; Korhonen et al. 2017). An alternative approach would be to scan already existing archive data for CME signatures. Our project to search Virtual Observatory spectra for CME signals started with a serendipitous detection of a CME on V374 Pegasi in observations we retrieved from the archives as auxiliary data to our photometric observing campaign – the spectra were obtained originally intended for Zeeman–Doppler imaging the magnetic topology of the star (Vida et al. 2016; Donati et al. 2006). For these events, detailed cloud modelling found later that all parameters are at the upper range of typical solar prominence parameters – except for temperature and area, which were found to be higher than for typical solar prominences observed in Balmer lines (Leitzinger, Odert, & Heinzel 2022).

Using the same database (the ESPaDOnS and NARVAL instrument archives proved to provide the most useful observations for our purposes), we extended our archive search for targets ranging from solar-type stars to late M-dwarves (Vida et al. 2019; Leitzinger et al. 2020). The obtained spectra – 3 700 hours (more than 43 000 spectra) for solar-like stars and 1 200 hours (5 500 spectra) for the late-type targets – revealed 478 line asymmetries

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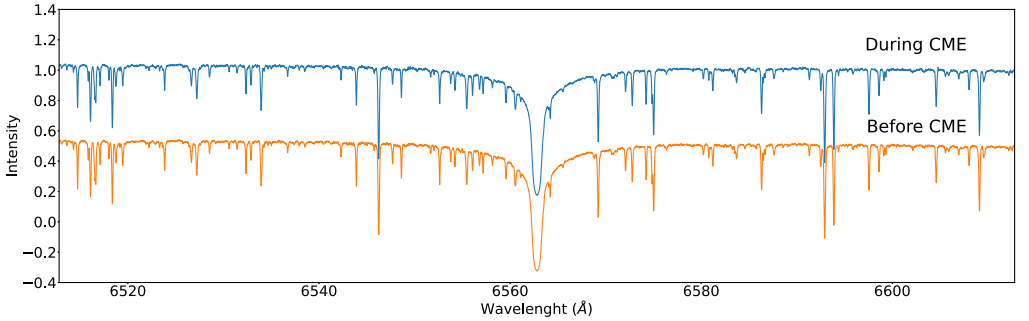


Figure 2. An example of the HARPS-N solar spectra before and during a strong solar coronal mass ejection on 2015 December 28 12:25 and 13:01. Unfortunately, no visible traces of the event are seen.

on the late-type targets with nine larger events; and no signatures of CMEs – only few flares – on the solar-like F–G–K sample. We determined that the rate of asymmetries in Doppler-signatures is correlated with magnetic activity indicators and inversely correlated with temperature, i.e., cooler, fast rotating stars with stronger magnetic fields tend to have more CMEs (see also Fig. 1). While this result might seem obvious – fast-rotating stars are known to have more flares – numerical simulations suggest that strong surface magnetic fields might be able to block the movement of the material in stellar coronae inhibiting CMEs and making successful ones slower (Alvarado-Gómez et al. 2018). This idea could be confirmed by the relatively low typical velocity indicated by the Doppler-shifts: the typical velocities were ≈ 200 km s^{-1}, whereas the surface escape velocity on these objects is ≈ 600 km s^{-1}. This suggests that most of the detected events are unsuccessful eruptions, with material falling back to the surface, or, alternatively, the observing method lets us only follow the earliest phases of the events in the Balmer lines.

The archive search yielded a much lower number of CMEs than anticipated: no events on the solar-like F–G–K sample (even though the on-target time should have yielded at least a few detections on the most active stars), and a CME rate 5–10 times lower on the late-type sample than we would expect from a scaled-up solar case.

3. Where are the stellar coronal mass ejections?

The low number of detections can be caused by lower intrinsic CME rates compared to the models (e.g. due to magnetic suppression), projection effects, or overestimated Balmer signatures because of the unknown plasma parameters of the stellar CMEs. Odert et al. (2020) calculated that the minimum observing time to detect CMEs on just moderately active stars can be over a few hundred hours. Based on the current observations the authors suggest that CME detection is more likely in mid- to late-type M dwarfs for two reasons: they require lower signal-to-noise ratio for a detection, and the fraction of observable-to-intrinsic CMEs is the largest. These objects, however, may need longer observing times than hotter stars with a similar activity level, as their predicted CME rates are lower. Based on our current knowledge, we might conclude the usual morale of the observing astronomers' paper: more observations are needed.

Beside extending the ongoing observing campaigns, an interesting possibility could be studying the Sun as a star. Currently, our Sun shows increasing activity in Cycle 25, which is expected to peak around 2025: during this time, we expect a higher number of flares and a higher CME activity, giving us an unprecedented opportunity to refine our knowledge on stellar CMEs as well. We plan to use high-resolution, high-cadence,

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public solar spectra (e.g. HARPS-N solar spectra†, see Fig. 2) and the data of solar satellites with in-situ CME measurements. With these observations we are currently developing a neural network to recognize solar CMEs in the spectra. The network will be used to analyze archival spectra possibly revealing events that would not be necessarily found by humans, on other stars. The solar spectra will provide a data set analogous to those obtained from other stars, but with the actual knowledge of solar CME times and the physical properties of the events from solar satellites. If this experiment proves successful, we can connect our exact knowledge of physical properties of the solar events to stellar data and extend the solar paradigm to stellar CMEs, possibly finding new CME indicators, and determine what magnitude of CMEs are observable on other stars.

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