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A Framework for Finding and Interpreting Stellar CMEs

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Abstract. The astrophysical study of mass loss, both steady-state and transient, on the cool half of the HR diagram has implications both for the star itself and the conditions created around the star that can be hospitable or inimical to supporting life. Stellar coronal mass ejections (CMEs) have not been conclusively detected, despite the ubiquity with which their radiative counterparts in an eruptive event (flares) have been. I will review some of the different observational methods which have been used and possibly could be used in the future in the stellar case, emphasizing some of the difficulties inherent in such attempts. I will provide a framework for interpreting potential transient stellar mass loss in light of the properties of flares known to occur on magnetically active stars. This uses a physically motivated way to connect the properties of flares and coronal mass ejections and provides a testable hypothesis for observing or constraining transient stellar mass loss. Finally I will describe recent results using observations at low radio frequencies to detect stellar coronal mass ejections, and give updates on prospects using future facilities to make headway in this important area.

Keywords. stars:flare, stars:activity, stars: late-type, radio continuum: stars

1. Overview

Stellar magnetic activity includes a whole gamut of observational signatures related to the presence and action of magnetic fields above the visible portion of the star's atmosphere. Stellar magnetic eruptions are the most dramatic releases of energy that a star on the cool half of the main sequence will undergo during its time on the main sequence. For a recent review of stellar flaring activity throughout the age of the solar system see Osten (2016). Solar physicists now recognize that a solar flare is only part of the eruptive event: a triad occurs in which the flare takes place low in the atmosphere, the coronal mass ejection takes place at much larger physical scales, and the energetic particles are the third component (Emslie *et al.* 2012). These all result from magnetic field reconfigurations and resultant reconnection and liberation of energy which goes into particle acceleration, plasma heating, mass motions, and shocks.

Astronomers have long been able to study stellar flares, starting from Hertzsprung's "peculiar nova of short duration" (Hertzsprung 1924). With advent of increasingly sensitive astronomical observatories at different wavelengths, we now see observational signatures of short-lived magnetic activity enhancements on stars across a large swath of

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the electromagnetic spectrum, from long wavelength radio waves (Konovalenko *et al.* 2012) to high energy gamma rays (Osten *et al.* 2007). Seeing multi-wavelength interrelationships between flare observables on stars as on the Sun (such as the Neupert effect; Hawley *et al.* 1995; Güdel *et al.* 1996)) firms up the conclusion that stellar flares are the same basic physical process as in solar flares, bolsters the comparison and extrapolation to stellar events, which can be up to 10^6 times more energetic (Osten *et al.* 2007) than the largest solar flare energies at about 10^{32} erg. Also, scaling relations established for solar flares which appear to extend to the stellar regime, as in the scaling between flare temperature and volume emission measure (Aschwanden *et al.* 2008), lend credence to the connection between solar and stellar flares.

2. Motivation

Current efforts to find Earth-like planets in the habitable zones of nearby stars are centering on nearby M dwarfs (Shields *et al.* 2016). The proximity to the star, with a habitable zone distance of less than 0.1 AU, renders these planets much more susceptible to the radiative and particle environment that the star creates. M dwarf stars in particular can produce frequent and extreme flares, and these have been the subject of astrobiological studies to examine the impact on an Earth-like planet in an M dwarf habitable zone. Khodachenko *et al.* (2007) examined the consequence of a high CME rate associated with that high flare rate. A high rate of coronal mass ejections could act like a dense, fast stellar wind, compressing the magnetosphere and exposing the planetary atmosphere to ionizing radiation.

CMEs are “geoeffective”, and energetic particles have the potential to influence planetary atmospheres. There are currently little to no observational constraints on these from a stellar perspective, and astrobiological studies take scaling relations from detailed solar studies and extrapolate, often by orders of magnitude, to the stellar cases (Segura *et al.* 2010; Venot *et al.* 2016). These extrapolations need to be empirically tested to confirm the validity of extrapolating to the more energetic regime of stellar events.

3. Solar Physicists’ Toolbox

Since their discovery in 1971, solar physicists have developed several methods of studying coronal mass ejections. The following is a brief review, to provide perspective on what tools might be applicable to the stellar case:

Direct Imaging via Thomson scattering

The coronagraph is the workhorse of solar CME observations (Howard 2011). Observations enable identification of the CME event in difference images, as well as determination of height-time progression. Measurements of velocity, mass, kinetic energy, potential energy, and acceleration can be made as well. See Yashiro *et al.* (2004) for a catalog of solar CMEs and derived properties.

Direct Imaging via Synchrotron Emission

Another somewhat novel solar observing technique is to directly image the synchrotron emission from a CME Bastian *et al.* (2001), resulting from the interaction of energetic particles (energies 0.5-5 MeV) with a magnetic field of 0.1 Gauss to a few Gauss.

Type II Bursts

Type II bursts have a strong association with CMEs (Gopalswamy 2006a; Gopalswamy *et al.* 2008a). A type II burst is coherent emission that is produced as the CME travels outward through the outer solar atmosphere. When the CME is super-Alfvenic, a shock is produced, and Langmuir waves produced as the result of the disturbance propagating through the solar atmosphere result in a drifting radio burst. The drifting radio burst reveals the location of the shock; as the density in the atmosphere changes, the characteristic frequency of emission changes. Often, two curves are seen in dynamic spectra of the variation of intensity as a function of time and frequency: these correspond to fundamental and harmonic emission from the MHD shock produced by the CME. Given knowledge of the run of electron density with height in the solar corona, the observed frequency drift can be used to constrain the exciter speed, which will be a lower limit to the CME velocity.

Scintillation of Background Radio Sources

Another technique utilizes the CME producing scintillation of background radio sources, as a means to study the ambient density at large distances from the Sun. Manoharan (2010) describes how the plasma disturbances change the large-scale structure of the heliosphere, and interplanetary scintillation remote-sensing observations can be used to study the CMEs and structures within them.

Coronal Dimming

Thompson *et al.* (2000) noted the association between coronal dimmings and CMEs. Dimmings are large-scale changes in the coronal intensity, and can occur during passage of a CME. These coronal dimming can also be seen in spectro-temporal observations (Harra *et al.* 2016); they primarily manifest at cooler solar coronal plasma (typical of the quiet Sun) than is seen during solar flares.

4. Detecting CMEs on Stars

The following is a non-exhaustive list of different methods which have been used to attempt to observe CMEs on stars. Studies often use the "unusual flare" approach, in which some departure of a given flare from the standard flare scenario is invoked as an explanation for seeing transient mass loss associated with a flare. Another issue is that many of these signatures are flare signatures, and it is necessary to find a signature that is associated uniquely with the CME and not the flare. But of course this is difficult due to the high degree of correlation between flares and CMEs seen (at least on the Sun).

High Velocity Outflows Seen in Emission Lines

High velocity outflows in principal are signatures of the escaping mass, which from solar CMEs can have maximum velocities near 3000 km s^{-1}. Houdebine *et al.* (1990) reported evidence for a ∼5800 km/s blueshifted outflow during a moderate flare on the M dwarf AD Leo; the outflow is a low level enhancement which is difficult to see above the quiescent emission. This requires the right orientation to see the maximum effect, and velocities of a few hundred km s^{-1} can be confused as originating from stellar flares. There have been no additional claims of high velocity outflows since Houdebine *et al.* (1990), despite signifiant spectro-temporal monitoring of optical and ultraviolet flare emissions (e.g., Kowalski 2012).

Pre-flare "dips"

Optical observations of stellar flares often see pre-flare diminutions in the light of the star prior to the start of the impulsive phase of the flare. Giampapa *et al.* (1982) reported perhaps the largest of these, with a decrease of about 25% of the stellar light prior to a large flare on the M dwarf EQ Peg. Much smaller dips (of order 1%) have recently been noted by Leitzinger *et al.* (2014) on flares in the Blanco 1 cluster with age of 30-145 MY. Such diminutions could result from the destabilitization of an off-limb filament, which deposits material into the disk line of sight. The concommitant increase in line and continuum opacity temporarily decreases chromospheric line emission, and Balmer continuum emission. This explanation requires a favorable geometry to work. Apart from this not being a unique CME signature, the decrease can also be explained as an increase in H^- opacity resulting from chromospheric heating during the flare.

Increase in X-ray Absorption During Flare

Spectral fitting of stellar coronal X-ray spectra must take into account absorption by intervening material. In low-resolution X-ray spectra, the low energy end of the spectrum must be attenuated by the amount of hydrogen column density N_H that the X-ray emission travels through. For the case of stellar coronal emission the intervening material is usually absorption by the ISM. Occasionally, such as the flare noted by Franciosini *et al.* (2001) in BeppoSAX observations of a large long duration flare on UX Ari, there is an excess amount of absorption seen early in the flare, which requires a higher N_H value than that attributable to the intervening ISM. In this particular event N_H increased by about a factor of five. Since it is variable, one explanation is that the extra absorption arises from an increase in circumstellar material, such as might happen from ejection of matter during a CME. These are incredibly rare, though, and questions about instrumental calibration effects at low energy have plagued this interpretation. There is now a sufficient databse of stellar flares seen with the Chandra and XMM-Newton satellite (thousands of flares reported in McCleary & Wolk 2011) that such an investigation could be launched from a statistical perspective.

Effect of CMEs on stellar environment

Melis *et al.* (2012) showed the rapid disappearance of a debris disk on timescales of $\sim$1 year, which was surprising and unexpected. The star, TYC 8241 2652 1, is a K2 dwarf with an age about 10 MY. As Melis *et al.* (2012) reported, grains present during observations in 2009 and before could be modelled as a characteristic size of $\sim$0.3 μm, temperature 450 K, 0.4 AU separation from the star, and total mass of 5×10^{21} g; they could not come up with plausible mechanism for removing this material. X-rays would be ineffective at heating grains of this size, requiring an X-ray luminosity L_x of 10^2-10^3 $L_\odot$, and flare energy $E\approx10^{39}$ erg. Osten *et al.* (2013) noted that grains smaller than 0.2μm would be radiatively ejected from the system, and investigated whether a CME would be sufficient to remove the grains. A flare could charge the dust grains in the debris disk, and with sufficiently small gyroradii they would be swept up by the magnetic plasma in the CME and removed. For the case noted by Melis *et al.* (2012), removing $\sim10^{21}$g in grains requires a CME with mass $\sim10^{20}$g, with a timescale for removal on the order of a few days. The sudden disappearance of emission from the debris disk material then would stem from a CME occuring along with a large flare; the flare could charge the dust grains, and then the CME and its magnetic field would sweep up the material and remove it from the disk. The timescale for the entire sequence would only take a few days. While other smaller scale bulk changes in debris disk emission have been noted, this has not yet been used as a diagnostic of CMEs, largely due to the paucity of young active stars with close-in warm debris disks which would be the most likely targets for such a phenomenon.

Observing stellar CMEs through scintillation of background radio sources

This is the astronomical equivalent to interplanetary scintillation used to study solar CMEs. Applying this to the stellar case requires a sufficient number of background sources at different distances from the star to have potential probes of scintillation as well as test particles farther out. As the source density of flat-spectrum radio sources is low, this would require a favorable target and patch of the sky to work, and would favor nearby stellar sources for a larger angular extent of the astrosphere.

Type II-like bursts associated with stellar flares

This technique has the best likelihood of yielding a detection or robust constraints, due to existence of new generation of low frequency telescopes and receivers which can enable wide bandwidth simultaneous observations to detect and diagnose events in a dynamic spectrum. The expected behavior of a radio source changing with frequency and time due to intrinsic motion rather than propagation effects can be written simply as

$$\frac{d\nu}{dt} = \frac{\partial \nu}{\partial n_e}\frac{\partial n_e}{\partial h}\frac{\partial h}{\partial s}\frac{\partial s}{\partial t} \tag{4.1}$$

where ν is the frequency of the burst at time t, n_e is the electron density, h is the radial height in the atmosphere and s is the path length traveled in the atmosphere. For a barometric atmosphere this reduces to $\dot{\nu} = \nu \cos\theta v_B/(2H_n)$, where v_B is the exciter speed whose motions cause the plasma radiation, H_n is the density scale height, and θ the angle between the propagation direction and the radial direction from the surface. For a source associated with plasma emission, these partial derivatives simplify, for a barometric atmosphere, to the second equation. Thus, given an observed frequency drift rate, frequency, and scale height (which can be estimated from X-ray observations), a constraint on the exciter speed is obtained.

Low frequency radio bursts have been seen from active stars: Konovalenko *et al.* (2012); Kundu & Shevgaonkar (1988); van den Oord & de Bruyn (1994) Drifting radio bursts in particular have been observed from nearby dMe flare stars, with a range of drift rates, as in Osten & Bastian (2006). The expected drift rate for coronal parameters of an active star, scale height H_n=2$\times$$10^{10}$ cm for a T$\sim$$10^7$ K, weakly super Alvenic shock gives drift rates of a few MHz s^{-1}, dependent on magnetic field strength and electron density.

Type II radio bursts are one particular example of a drifting solar radio burst, and based on solar observations, are the current best candidates to search for signatures of stellar transient mass loss. Large flares should have a large CMEs occurring along with them. While the overall rate of type II bursts is low, the association rate increases with CME speed. Therefore the fastest, most energetic CMEs should have type IIs associated with them. Yashiro *et al.* (2006) showed a 100% association between large solar flares and large CMEs; while only $\sim$10% of solar CMEs overall show decimetric type II bursts (Gopalswamy 2006b), the Type II burst association with CME increases with increasing CME speed (Gopalswamy *et al.* 2008b).

The LOw Frequency ARray, LOFAR, and the Jansky Very Large Array, are two new radio facilities that can be used to try to detect stellar CMEs. LOFAR expands the frequency range of sensitive interferometric capabilities to frequencies between 10 MHz and 200 MHz. The upgrade of the JVLA's low frequency receivers expanded the bandwidth by about a factor of 10.

Initial searches, reported by Crosley *et al.* (2016), did not see any evidence for bursting behavior. Figure 1 shows the range of parameter space that we have constrained where we would have seen emission – the X axis is the source size, and the y axis is the brightness temperature. Figure 1 also shows the expected burst shape in frequency and time, based on a couple of different assumptions bout the magnetic field strength and density. We are just barely sensitive with these observations to a very large solar-like type II burst. This was based on 15 hours of observations of a highly active dMe flare star, during which time we expected to see about 5 flares and associated CMEs.

Connecting Flares and CMEs

Using statistical associations between flares and CMEs is the next most promising approach to understanding stellar transient mass loss, as stellar flares are commonly observed in many wavelength regions. Numerous observations of solar and

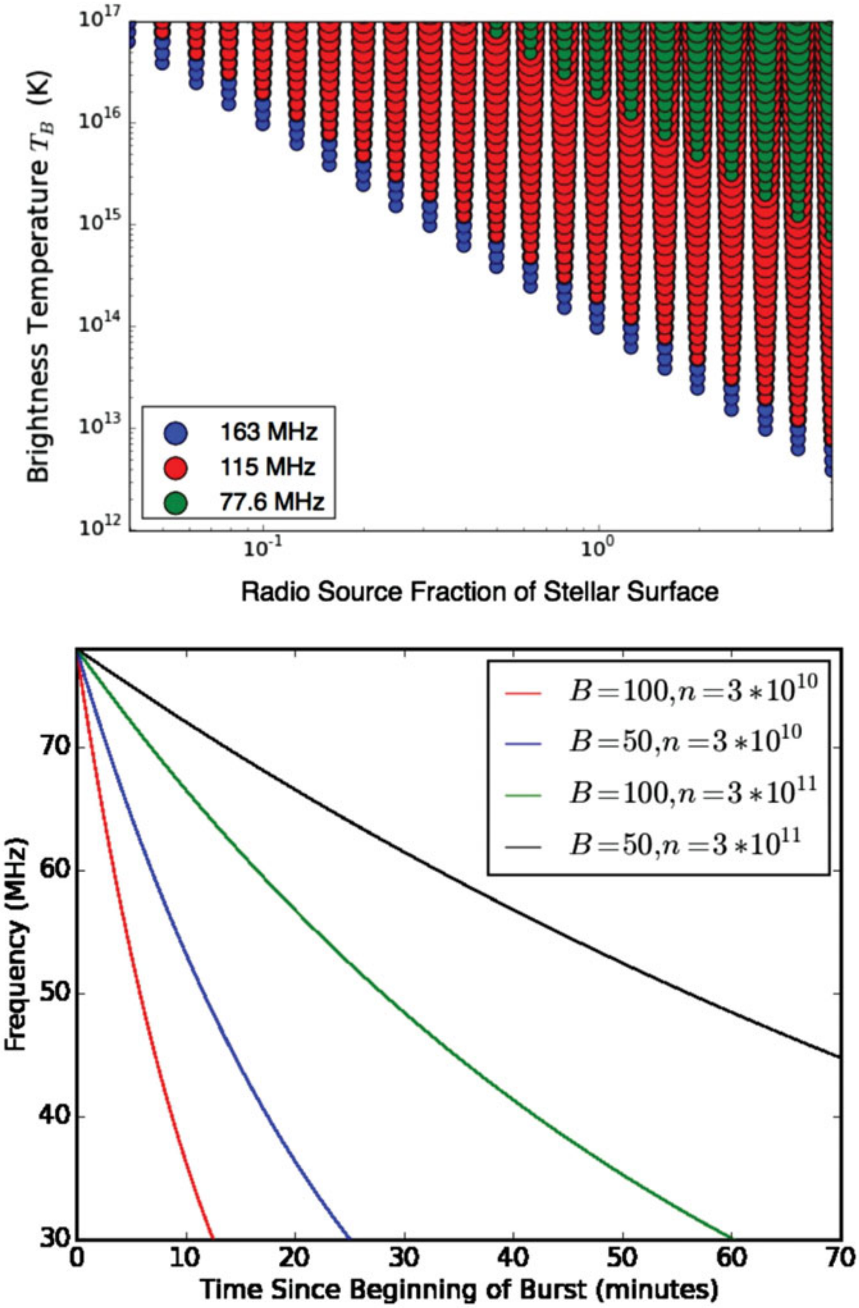

Figure 1. *(top panel)* Figure 5 from Crosley *et al.* (2016), showing region of parameter space constrained by the lack of detection of type II stellar bursts at low frequencies in 15 hours of observation. Typical brightness temperatures of solar type II bursts are $\sim 10^{14}$K. The current sensitivities in the stellar case permit ruling out very large and high brightness temperature events. *(bottom panel)* Figure 6 from Crosley *et al.* (2016), showing expected path in the frequency-time space for a type II burst. The magnetic field strength and electron densities shown are valid from constraints on the plasma properties of active M dwarfs, and set the speed expected for a slightly super-Alfvenic (1.2 M_a) shock.

stellar flares show commonalities, which suggests a similar origin Solar eruptive events show scalings between solar flares and CMEs, which if applied to stellar flares & CMEs could be a powerful (& relatively easy) way to probe stellar eruptive events Emslie *et al.* (2012) studied 38 solar eruptive events and determined the energetics of various components. They found that the bolometric radiated flare energy showed a good correlation with CME energy (kinetic + potential). Additionally, empirical solar CME mass - flare energy scalings have been established, from Aarnio *et al.* (2011, 2012) and Drake *et al.* (2013) Both papers find a relation of the form $M_{\mathrm{CME}} \propto E_{\mathrm{GOES}}^{\beta}$, with $\beta \sim 0.6$. Drake *et al.* (2013) additionally determined an empirical relationship between CME kinetic energy and flare radiated energy in the GOES 1-8 Å bandpass for solar flares. These relationships can in principle be extended to the stellar flare energy regime, and predict quite massive CMEs, but potentially requiring about an order of magnitude more energy in the coronal energy budget.

Osten & Wolk (2015) used the approximate equipartition between CME kinetic energy and flare bolometric radiated energy in the Emslie *et al.* (2012) study to explore the implications for transient mass loss. Applying this technique to stellar flare frequency distributions requires having a way to correct the flare radiative losses in a particular band to determine the total bolometric radiated energy losses, which Osten & Wolk (2015) did. The relatively simple equation is then

$$1/2 M_{\mathrm{CME}} v^2 = E_{\mathrm{rad}}/(\epsilon f_{rad}) \tag{4.2}$$

where M_{CME} is the CME mass, v is the CME velocity, E_{rad} is the radiated flare energy in a particular bandpass, ϵ is the equipartition factor, and f_{rad} is the fraction of the bolometric flare radiated energy that appears in the bandpass under consideration. Then the observed flare frequency distributions can be related to an inferred rate of mass loss associated with the flares, and this method can be applied to any wavelength range where the fraction of total flare energy in that bandpass can be estimated. Osten & Wolk (2015) applied this to published flare frequency distributions of several different types of magnetically active stars. For the case of two nearby well-studied M dwarf flare stars, AD Leo and EV Lac, which had flare frequency distributions in the optical and at coronal wavelengths, consideration of the partition fraction f_{rad} for optical and coronal wavelengths, respectively, leads to a similar value of estimated stellar mass loss. The overall rates of stellar mass loss are quite high, 10^{-11} $\dot{M}_{\odot}$ yr^{-1}, for these M dwarfs. The same issue as found by Drake *et al.* (2013) is present here, and the resolution awaits definitive constraint on the detection of stellar coronal mass ejections.

5. Do Stars Produce Coronal Mass Ejections? Can we observe them?

The solar perspective is useful to establish scaling relations which can potentially be extended to the much enhanced energetics of active stars. However, it can also be the source of some cautionary tales for such interpretations. the solar active region 12191 in the fall of 2014 produced many X-class flares but few CMEs. Sun *et al.* (2015) suggested that large overlying fields above the active region may have prevented breakout or eruption. Active stars are known to have large magnetic field strengths on their surfaces, and it would not be out of the realm of possibility that this might lead to arcades of strong magnetic fields which would prevent material from lower in the stellar atmosphere from escaping. Proving a negative is difficult, however, but observationally based methods to constrain the rate of stellar coronal mass ejections is a needed next step.

6. Conclusions

There are many ways to try to observe stellar CMEs; all have some kind of bias associated with them. The solar perspective is needed especially to interpret potential observational diagnostics of stellar CMEs. The stellar perspective is also needed to reveal what is feasible as a method without spatial resolution and exquisite sensitivity. In addition, stellar studies continue to reveal the differences between our well-studied Sun and the panoply of stars, which needs to be folded in to this study as well.

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Discussion