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Slowly Rotating M Dwarfs with Unusually Strong Magnetic Fields: Interpreting the Data in Terms of How Stars Acquire Fields and How They Lose Fields

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Abstract

L. T. Lehmann et al. (2024, hereafter L24) have reported on the presence of "unusually strong" (20-200 G) large-scale magnetic fields in six M dwarfs: four of the stars are probably completely convective, while two of the stars are probably only partially convective. A striking feature of all six stars is that they are all unusually slow rotators, with rotational periods of 40–190 days. Remarkably, L24 report that the field strengths on these six slow rotators are "similar to those of M dwarfs rotating significantly faster." One further M dwarf (YZ Ceti) which combines slow rotation with an even stronger field (276 G) has recently been reported by A. Biswas et al. To account for these strongly magnetic but slowly rotating stars, L24 have suggested that dynamos in the slow rotators (by means of which the stars *acquire* magnetic fields) must be operating in a different regime from that which operates in faster rotators. Here, I suggest an alternate hypothesis based on two apparently independent results in the literature: (1) the presence of "rugged invariants" in magnetohydrodynamic turbulence, and (2) the paucity of empirical evidence for coronal mass ejections from flare stars. In the case of the six "unusually strong-field" stars in the L24 sample, I hypothesize that, as well as considering how stars acquire magnetic fields, it is also important to consider the processes by which those stars lose magnetic fields.

Unified Astronomy Thesaurus concepts: Magnetohydrodynamical simulations (1966); Flare stars (540); Stellar coronal mass ejections (1881)

1. Introduction

The most common types of stars in the solar neighborhood are dwarfs of spectral type M. For example, in a catalog based on Gaia ERD3 and Hipparcos data containing objects within a distance of 25 pc of the Sun, A. Golovin et al. (2023) state that "about 72%" of the 5230 stars which have been identified are M dwarfs. Dwarf stars of spectral type M are best known for their tendency to flare frequently. By analogy with flares in the Sun, stellar flares are assumed to be powered by magnetic free energy, i.e., the excess energy over and above the energy of a potential field. In the Sun and in other stars, magnetic free energy can accumulate when fields near the surface are stressed by turbulent convective motions, leading to twisted/knotted fields which are characterized by a physical quantity known as "magnetic helicity."

From a strictly *theoretical* point of view, it has been believed for almost seven decades (e.g., D. N. Limber 1958) that the internal structure of M dwarfs undergoes a significant physical alteration as we move from "early" type stars (with spectral types near M0) to "later" types (later than M2-M3). On the one hand, models of early M dwarfs predict a (more-or-less deep) outer convective envelope plus a radiative core. In such "partially convective" models, a well-defined "interface region" is predicted to exist between radiative and convective zones. On the other hand, theory also suggests that later M dwarfs are completely convective, with no trace of an interface region.

Although the theoretical work on M dwarfs is well established by many independent stellar structure codes, it is still worthwhile to raise an issue which an anonymous referee posed to me in 2015: is there empirical evidence which supports the theoretical prediction that M dwarf stars become completely convective at a certain spectral type? In dealing with stars of earlier spectral type, especially those similar to the Sun, helio/asteroseismic data (i.e., p-mode pulsation frequencies) have been successfully used to determine the depth of the convective envelope in the Sun with a precision of order 1% (e.g., J. Christensen-Dalsgaard et al. 1991); these results confirm that stellar structure codes do a good job computing the internal structure of solar-like stars. However, in the case of M dwarfs, the situation is different: C. Rodriguez-Lopez (2019) reports that "a clear detection of a pulsating M dwarf has not yet been achieved." Very recently, R. G. De Amorim et al. (2026) reported that an M0-M2 dwarf may be a candidate for a pulsator although they conclude that "the detection of a pulsating M dwarf has not yet been achieved." As a result, asteroseismic studies cannot yet provide reliable empirical proof of the depth of the convection zone in M dwarfs.

Using data which do not depend on asteroseismic measurements, some empirical support for the theoretical prediction of the above-mentioned structural transition in M dwarfs has become available. We summarize the relevant data in Section 2.

Why is it necessary to discuss the internal structure of M dwarfs in the present paper? Because to understand chromospheric/coronal "activity" in such stars more completely (especially their association with magnetic fields), it is beneficial to identify physical processes which could cause a star to acquire such magnetic fields. In Section 2, a summary of dynamo theory as it applies to cool dwarfs is presented. However, in the present paper, the goal is not to focus only on how stars acquire fields; instead, in Sections 3–6, precisely the

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opposite question will be posed. Namely, by what process(es) does a star lose its magnetic field? I explore the hypothesis that if a star cannot readily lose its field, then that star may evolve into a condition where its rotation has been slowed down significantly even though the field remains strong.

A key aspect of the hypothesis of the present paper concerns the role that is played by a physical quantity introduced by L. Woltjer (1958): in a closed magnetic system, the dot product $A.B$ (where A is the magnetic vector potential, such that B = curl A), when integrated over the volume of the system, is invariant if the medium is dissipationless. This invariant was subsequently referred to as the "degree of magnetic knottedness" (H. K. Moffatt 1969) or as "magnetic helicity" (e.g., U. Frisch et al. 1975), although Woltjer did not use either of those terms in his 1958 paper. M. A. Berger & G. B. Field (1984, hereafter BF84) also used the terms twisting, kinking, linking, knotting, and writhing to explain the physical aspects of what is meant by magnetic helicity. Also BF84 stressed that in a system (such as the Sun or any star) which is not strictly closed, it is nevertheless meaningful to refer to a quantity known as the relative magnetic helicity; this is the quantity which is currently used to assign a particular local value of helicity to each active region in the Sun. It is particularly relevant to the present argument to note the following empirical result: an active region where the amplitude of the (relative) magnetic helicity is found to be large is more likely to generate coronal mass ejections (CMEs). This is discussed further in Section 5.

Although the present paper does not deal with massive stars, it is worth noting that such stars may acquire fields that are "frozen in" from the magnetized interstellar medium. In such stars, electrical conductivities may be so large that the primordial field may survive for periods of billions of years (e.g., T. S. Smith 1964), i.e., throughout the main-sequence lifetime of such stars. But this mechanism is probably not available to low-mass stars; their formation process may contain a period of complete convection (in the Hayashi pre-main-sequence phase). Convective motions in the Hayashi phase may lead to rapid decay of the field as it becomes tangled in the turbulence. In view of this, it seems that only processes which actively generate (and regenerate) fields in situ can explain the fields which are responsible for present-day flares in M dwarfs. Dynamos are natural candidates for such processes.

2. How Do Cool Dwarf Stars Acquire Magnetic Fields?

The leading candidates for processes which cause a star to acquire a field are considered to be dynamos. Two types of dynamos are considered to be capable of operating in cool dwarf stars: (i) one type operates if a convective zone and a radiative zone are both present in the same star, and (ii) a different type of dynamo operates if a zone of convective turbulence occupies a significant fraction of the radius of the star. In some stars, both types of dynamos may be operating simultaneously, in which case local conditions determine which type is dominant.

In this section, empirical evidence will be presented to support the widespread belief that cool dwarfs of spectral class K and M generate fields via dynamo action. Of particular interest are stars which flare.

Stellar flares are more-or-less dramatic short-lived brightenings with rapid rise times and slower decay times; they may last from as little as a minute (or less) to as long as hours. By analogy with solar flares, the short-lived releases of energy in cool dwarfs were attributed to magnetic energy for many years before spectroscopic polarization data successfully proved the existence of magnetic fields on the stellar surface and measured the field strengths on those stars. However, flares are not the only avenue by which magnetic fields in stars release energy; the energy associated with magnetic fields in any particular star can also be converted in less dramatic fashion in such a way as to provide a long-lived supply of heat to a chromosphere and a corona in that star. As a result, quantifying the emission from the nonflaring ("quiescent") chromosphere and/or corona of a star can also serve as a proxy for magnetic fields in that star.

A significant question will arise in the course of discussing the search for the transition between partially and completely convective stars: is this transition to complete convection (TTCC) more easily detectable by using chromospheric data or by using coronal data? This will be discussed at the end of Section 2.3.

2.1. Dynamos in Cool Stars

B. R. Durney et al. (1993, hereafter D93) have described how a certain type of dynamo may operate in the interface region of a rotating solar-type star. The stellar angular velocity Ω, along with the radial or latitudinal variation in Ω from one part of the star to another (i.e., differential rotation), plays a key role in the operation of this dynamo. In order for the dynamo to be effective, a second physical process must also be operative in the star: this is referred to as the "α-effect," which quantifies how poloidal field can be generated from the toroidal field as a result of Coriolis forces in the convective flow in a rotating star. D93 refer to a dynamo which relies on both Ω and the α-effect as an "$\alpha\Omega$-dynamo." Because of the important role that is played by rotation in the $\alpha\Omega$-dynamo, the outcome of such a dynamo is expected to be quite sensitive to Ω. That is, the magnetic field strength (and the accompanying evidence of "magnetic activity") is expected to increase steeply as the rotational speed increases. Thus, if the "rotation–activity correlation" (RAC) can be determined in a star where an $\alpha\Omega$-dynamo is operating, the RAC is expected to have a steep positive slope.

However, in addition to the $\alpha\Omega$-dynamo, D93 point out that a second type of dynamo can also operate in a turbulent medium. In this dynamo, the α-effect dominates, while rotation contributes in a way that D93 describe as "not essential" except for increasing the rate of generation of the dynamo field. Such a dynamo (with only a weak dependence on rotation) is referred to as an α^2-dynamo. In such a dynamo, the magnetic field strength (and the accompanying evidence of "magnetic activity" in the form of emission in the cores of the Ca II H and K lines) is expected to be less sensitive to Ω than is the case in the $\alpha\Omega$-dynamo. That is, the RAC for a star where the α^2-dynamo dominates should still show some positive correlation with Ω, but the slope of the RAC is expected to be shallower (i.e., less steep) than in the case of a star where an $\alpha\Omega$-dynamo is operating.

Can the slope of the RAC help to distinguish between different dynamo modes in different low-mass stars? This paper will refer to two different datasets which may be helpful in addressing this issue: one dataset is chromospheric, the second is coronal. Consider the chromospheric data first.

2.2. Chromospheric Emission in Ca II H and K Lines

E. R. Houdebine et al. (2017, hereafter H17) measured the flux F of chromospheric emission in the core of the CaII H and K resonance lines in 418 cool dwarfs with spectral types K4 to M4. H17 also used spectra of all stars which had sufficient signal/noise to extract the (projected) rotational velocity v sin i. By plotting log F versus log $(P/\sin i)$ (where $P = 2\pi R/v \sim 1/\Omega$), H17 determined the RAC slope.

H17 divided their sample of stars into active (K4e-M4e with Hα in emission) and inactive (K4-M4) groups; all stars possessed emission cores in the CaII lines.

H17 found that the inactive stars exhibited a shallow RAC slope (≈0.6–0.8) over the entire spectral range of their sample (K4 to M4). The shallow slope is consistent with an α^2 dynamo operating in the deep convective envelope. Note that, in a star where the depth of the convective envelope is (say) "only" $0.5R^*$, convection occupies 7/8 of the star's volume; there is only about 10% difference between 7/8 (≈88%) of the stellar volume and 100% of the volume (as in a fully convective star). Therefore, an α^2-dynamo can operate almost as effectively in a star where the convective zone depth is "only" $0.5R^*$ as in a fully convective star.

In contrast, however, H17 found that the active stars with "earlier" spectral types (K4e-M2e) exhibited a different behavior in their RAC slopes: the slope was found to be ≈1.4–1.9, i.e., significantly steeper than for the inactive stars. H17 proposed that this enhanced steepness may be due to an $\alpha\Omega$ dynamo operating in the radiative–convective interface in these partially convective stars. On the other hand, the active stars with "later" spectral types (M3e-M4e) revealed an RAC slope which overlaps with the inactive star slope; H17 concluded that the TTCC occurs between M2 and M3.

Before switching from chromospheric data to coronal data, it is worth noting an important result of H17: the ratio of coronal emission to chromospheric emission increases by a large factor in going from K4 stars to M4 stars. Specifically, if two stars with spectral types K4 and M4 have identical values of $F = 10^{27.5}$ erg s^{-1} in CaII emission, the X-ray flux emitted by the M4 star is on average 110 times larger than the X-ray flux from the K4 star. H17 suggested an explanation for this behavior based on electrodynamic resonance in coronal loops (D. J. Mullan 1984). J. L. Linsky et al. (2020) have suggested other possible explanations.

2.3. Coronal Emission in X-Rays

N. J. Wright et al. (2018, hereafter W18) reported X-ray luminosities L_x in a sample of 19 slowly rotating M3-M6 (fully convective) dwarfs where the coronal temperatures may be as large as 20 MK. To create such hot coronae, magnetic effects are almost certainly at work. W18 used their data to construct a "rotation–activity relation (RAR)" (analogous to our RAC) which might provide information about stellar dynamos. To create the RAR, W18 plotted L_x/L_{bol} versus Rossby number $Ro = P_{rot}/\tau$, where P_{rot} is the rotation period, and τ is the convective turnover time. W18 included information in the literature about partially convective stars.

The RAR obtained by W18 (see their Figure 3) contains two distinct segments: at short rotation periods ($Ro \leqslant 0.1$, P_{rot} <10–30 days), the RAR is flat (i.e., saturated); at longer rotation periods, $L_x/L_{bol}$is unsaturated, decreasing as P_{rot}/τ increases. All 19 stars in the W18 sample occupy the unsaturated regime.

As regards similarities between W18 and H17, we note that the existence of two segments in the coronal RAR (saturated and unsaturated) overlaps with the behavior reported by H17 for the chromospheric RACs of M3 and M4 stars. Since M3/M4 stars are probably fully convective, and W18 specifically selected fully convective stars, this overlap in the W18 and H17 results is encouraging. However, H17 found that chromospheric saturation in their K4-M2 stars does not set in until P_{rot} is shorter than 2–5 days. This distinctly different behavior of the onset of saturation in chromospheric and coronal data may be related to the discussion in Section 2.2 (last paragraph).

W18 emphasized the following conclusion: the coronal RAR for fully convective stars is "indistinguishable from that of partly convective stars." For a possible explanation for such behavior, see Section 2.2 (third paragraph).

W18's conclusion in the preceding paragraph has an important corollary: the use of coronal data alone is not particularly effective at identifying the TTCC. Since stars on both sides of the transition have similar X-ray properties, L_x data do not provide any noticeable "feature" at the transition. This agrees with the statement "the L_x/L_{bol} ratio remains essentially invariant over the spectral range from early M to at least M7" (T. A. Fleming et al. 1993).

The empirical invariance of coronal emission as a function of spectral type in the vicinity of the TTCC is quite different from the behavior of chromospheric emission. As mentioned in Section 2.2, the discovery of a significant change in the chromospheric RAC slope in stars with spectral types between M2 and M3 provides us with a significant "feature" of the TTCC.

In discussing their results, W18 made a point of emphasizing the following conclusion: the RAR which they derived for fully convective stars is "indistinguishable from that of partly convective stars." A possible explanation for such a result has been given in the conclusion (C4) in Section 2.2.

However, an important consequence of the W18 conclusion is the following: in attempts to identify the TTCC, the reliance on specifically coronal data alone appears to be not particularly effective. The problem is that, as W18 emphasize, stars on both sides of the transition have similar X-ray properties. As a result, coronal data do not exhibit any noticeable "feature" at the TTCC. I believe that this lack of a "feature" helps to explain a puzzle which was first noted in ROSAT X-ray data more than 30 yr ago by T. A. Fleming et al. (1993): "the L_x/L_{bol} ratio remains essentially invariant over the spectral range from early M to at least M7."

This invariance of coronal emission as a function of spectral type reported by T. A. Fleming et al. (1993) and by W18 in the vicinity of the TTCC is very different from the behavior of chromospheric emission as one passes through the spectral type where the TTCC occurs. As mentioned in Section 2.2, the discovery of a significant change in the chromospheric RAC slope in stars with spectral types between M2 and M3 seems to provide a plausible signature of the TTCC.

3. How Do Stars Lose Magnetic Fields?

Just because a star is able to generate (by dynamo action) a magnetic field at a certain stage of evolution, it does not mean that the star will retain that field at all subsequent stages of

evolution. Fields may diffuse away as time progresses. Even in the simplest case, e.g., a static field in an object with characteristic length-scale L and electrical conductivity σ (in electrostatic units), the field undergoes decay on a timescale $\tau_D \sim \sigma L^2/c^2$. This timescale characterizes the time required for ohmic losses per unit volume "to dissipate an amount of energy comparable to the magnetic energy $B^2/8\pi$" contained in the unit volume (e.g., R. J. Bray & R. E. Loughhead 1964, hereafter BL64).

In a completely ionized gas, L. Spitzer (1956) found that σ scales with temperature T as $T^{3/2}$ lead to $\sigma \approx 10^{16}$ e.s.u. in the solar corona. In the photosphere of a sunspot umbra, where the gas is mostly neutral, σ is orders of magnitude smaller than in the corona: $\sigma \approx 10^{11}$ sec^{-1} (BL64, p. 270). Using the latter value, in a sunspot with diameter 1500 km, the photospheric field could diffuse away in about 1 month. In coronal gas, an object with the same diameter could preserve its field against diffusion for thousands of years. If the fields are nonstatic, e.g., if suitable gas motions are present, then these timescales can be reduced.

The key aspect of these results is that diffusive decay of magnetic fields can in principle be reduced to ever shorter timescales if the relevant length-scale L can be made ever smaller. In this regard, a significant contribution to field decay in a plasma occurs when the plasma is turbulent. In Section 4, consideration is given to some physical processes which occur in MHD turbulence and which have a bearing on important aspects of stellar activity.

4. Magnetic Energy: How Does It Decay in MHD Turbulence?

MHD turbulence can be studied in the laboratory, especially in devices which are designed for purposes of nuclear fusion. However, beyond the laboratory, attempts to explain coronal heating in the Sun have shown that MHD turbulence (powered by convective turbulence near the solar surface) may contribute a key role (e.g., W. H. Matthaeus et al. 1999). By implication, stars which possess coronae (e.g., flare stars) are also expected to be sites of MHD turbulence. Certain properties of such turbulence are important in the context of the stars which are discussed in the present paper.

In (nonmagnetic) hydrodynamic turbulence, where kinetic energy is contained in multiple eddies, it is known that eddies range in size from large to small. Analogously, in MHD turbulence, fluctuations in the magnetic field also span a range of length-scales. Numerical modeling of 2D and 3D MHD turbulence (e.g., A. Pouquet et al. 1976) indicates that the energy in magnetic field fluctuations undergoes a "forward cascade" from large scales toward smaller scales (this process is analogous to the behavior of kinetic energy in hydrodynamic turbulence: the kinetic energy cascades to the smallest scales). As a result, some magnetic energy is continually being transferred to the smallest scales where diffusive processes (occurring on time scales $\sim L^2$) have an opportunity to occur more and more rapidly. The process known as magnetic reconnection also operates most rapidly at the smallest length-scales, causing the magnetic field energy to be converted into localized heating.

The most striking observational consequence of magnetic decay is that magnetic energy is released into the local gas, causing an event which may be detectable by observations in the visible or ultraviolet bands or X-rays as a transient (thermal or nonthermal) emission (i.e., a flare). Flares are the most striking evidence for the decay of magnetic energy in the Sun. Their intrinsically magnetic nature is confirmed by the observed fact that flares occur $\sim$100 times more frequently at the so-called "solar maximum" than at the so-called "solar minimum") (D. J. Mullan 2023, p. 341). In this regard, the relevant aspect about sunspots is that in the umbra, the magnetic field reaches strength of several kilogauss; such strong fields are never observed on any other region of the solar surface. The umbral fields are so strong that they can powerfully suppress convective speeds (by a factor of $\sim$20) compared to the speeds which occur in convective granules in the quiet Sun (D. J. Mullan 2023, p. 262).

5. Magnetic Helicity: a Distinctive "Rugged Invariant" of MHD Turbulence

In the context of solar physics, by measuring the 3D structure of the magnetic field in a particular solar active region, a numerical value of the relative magnetic helicity H_m (see Section 1) can be derived for that active region (e.g., E. Pariat et al. 2015). Data indicate that active regions differ from one another as regards the value of H_m, just as they differ from one another as regards the number and size of sunspots. Why do different values of helicity occur in different active regions? Part of the answer is that before a flux rope appears on the solar surface (thereby creating an active region), the flux rope must first survive its passage through the convective turbulence; that turbulence can seriously shred a flux rope unless there is sufficient twist (helicity) to preserve the identity of the flux rope (F. Moreno-Insertis & T. Emonet 1996). As a result, when an active region first emerges on the solar surface, it already possesses a finite amount of helicity. Subsequently, convective jostling near the solar surface leads to extra twisting of the magnetic fields; this process adds to, or subtracts from, the initial twist, depending on the direction of convective motions.

Since H_m is an algebraically signed quantity, some active regions have positive (right-handed) H_m while others have negative (left-handed) H_m. Moreover, in an empirical result which does not seem to have been predicted in advance, the empirical data show that, in the northern (southern) hemisphere of the Sun, more than one-half of all active regions exhibit negative (positive) H_m. Simulations which attempt to explain this empirical result have been reported (N. Brummell et al. 2023).

If the turbulence occurs in a medium which has infinite electrical conductivity (i.e., zero resistivity), the physics of such nonresistive MHD is said to be "ideal." In ideal MHD, H_m is strictly conserved, and is referred to as a "rugged invariant." A second "rugged invariant" is the total energy E (kinetic plus magnetic). A third rugged invariant is the cross helicity involving the velocity vector and the magnetic field vector; the third invariant will not be mentioned further in this paper.

When the MHD turbulence is nonideal, the values of E and of H_m both undergo decay at finite rates. However, it is crucial for purposes of the present paper that E and H_m do not decay at the same rate. J. B. Taylor (1974) conjectured that, in nonideal MHD, H_m should decay more slowly than the magnetic energy decays. The reason for this conclusion rests on a particular aspect of MHD turbulence: H_m does not experience the well-known forward cascade of magnetic (or kinetic) energy toward smaller length-scales. Quite the contrary: H_m is found to undergo turbulent cascade toward larger scales, i.e., an

"inverse cascade." Thus, while E is undergoing a process which provides access to the shortest length-scales (thereby facilitating rapid dissipation), H_m does not have such ready access to short scales. While magnetic (and kinetic) energy may be undergoing more-or-less rapid decay, the distinct quantity H_m appears to be (relatively) shielded from the traditional source of decay. As a result, H_m appears as a (relatively) conserved quantity even in nonideal MHD. In a study of the solar corona, M. A. Berger (1984) showed that "helicity decay occurs on a diffusion timescale which is far too great to be relevant to most coronal processes." In Section 6, suggestions by D. M. Rust (1994) and by B. C. Low (1996) as to how the Sun manages to lose helicity in a nondiffusive manner will be discussed.

Taylor's conjecture means that in a turbulent magnetized medium, magnetic energy may well be undergoing decay, but magnetic energy cannot simply decay in an arbitrary manner as time goes on. Instead, at all times, the decay of magnetic energy is subject to a certain constraint, namely, the medium must simultaneously ensure that H_m is (essentially) conserved, and the more strictly H_m is conserved (for whatever reason), the more constrained will the decay of magnetic energy become. In the ultimate limit of complete conservation of H_m (if such can happen), the magnetic energy may be constrained to remain close to its original value for a time that is much longer than the formal diffusion timescale τ_D would lead one to expect.

I suggest that, if empirical evidence can show that H_m is in fact not being lost by a star (see Sections 7–9), then Taylor's conjecture could shed light on the conundrum of the strong fields in slow rotators which have been reported by L24 and A. Biswas et al. (2026, hereafter B26).

6. How Does the Sun Lose Helicity?

The Sun undergoes an 11 yr cycle during which the global field of the Sun reverses sign. In order to make way for the new cycle fields, the old cycle fields (which point in the "wrong" direction) must be removed. The hypothesis proposed by H. W. Babcock (1961) is a plausible mechanism for switching the sign of the Sun's global field. Also at work on a more local level, flares provide an effective process to reduce the magnetic energy which the Sun accumulates in certain active regions in the course of one 11 yr cycle, again assisting to some extent in getting ready for the new cycle.

But what about the helicity of the Sun's magnetic fields? How does the Sun rid itself of any excess old-cycle helicity in preparation for acquiring the new-cycle helicity? D. M. Rust (1994) and B. C. Low (1996) offered arguments which suggest that the Sun expels helicity by means of CMEs. A CME is observed to occur from time to time as a more-or-less large amount of magnetized solar plasma is raised up above the surface and, after detaching from the Sun, propagates outward through interplanetary space. The rate of CME occurrence per month is observed to be typically 30–40 times larger at solar maximum than at solar minimum (D. J. Mullan 2023, p. 377). This indicates that, for CMEs (as for flares), magnetic effects certainly play an important role.

However, despite this common dependence of flares and CMEs on magnetic effects, it is essential to note that, empirically speaking, there does not exist a one-to-one correlation between flares and CMEs; that is, not every solar flare is accompanied by a solar CME, nor is every solar CME accompanied by a solar flare. An analysis by M. Youssef (2012) is quantitatively pertinent here. Using a classification system based on the measurement (by the GOES spacecraft) of the peak X-ray emission from each flare, M. Youssef (2012) reported that the percentage of solar flares that are accompanied by a solar CME is as large as 90% in the largest solar flares (belonging to the so-called X-class). However, M. Youssef (2012) significantly also reported that, in smaller solar flares, the percentage of such flares that are accompanied by a solar CME is only 29%. To be precise, the term "smaller solar flares," as used by M. Youssef (2012), refers to flares that are assigned (based on GOES data) to C-class; in such flares, the peak X-ray emission reported by GOES is 100 times smaller than the peak X-ray emission reported by GOES in X-class flares. One other aspect of Youssef's results is important to highlight here: even though X-class flares are indeed more effective at generating CMEs, there are nevertheless some X-class flares (about 10% of them) which are not accompanied by CMEs. An example of this behavior reported by A. G. M. Pietrow et al. (2024) will be discussed in Section 8.

Therefore, it is important to ask what the difference is in the ways that magnetic effects generate on the one hand flares and on the other hand CMEs. For flares, as mentioned above, the magnetic energy (and its dissipation) plays a major role.

But what about CMEs? A remarkable observational study of 133 large solar flares by M. D. Andrews & A. Nindos (2004) showed that if an active region possessed large magnetic helicity H_m (i.e., if the fields in that active region are strongly twisted/knotted), a flare in such a region is more likely to be accompanied by a CME. But if the active region possessed only small H_m, it is less likely that a CME will be associated with a flare (for details about similar conclusions derived from other studies of various active regions, see D. J. Mullan 2023, p. 379). This result confirms the following conclusion: the magnitude of H_m in a solar active region determines the probability that CMEs will be launched from that active region. This confirmation supports the suggestions of D. M. Rust (1994) and B. C. Low (1996) that CMEs do play a role in removing magnetic helicity from the Sun.

A further possible difference between flares and CMEs is that flares require the presence of finite resistance to occur; a flare is an intrinsically dissipative phenomenon and can therefore not occur in a perfectly conducting medium. On the other hand, CMEs may in principle occur in ideal MHD conditions, i.e., even if the resistivity of the plasma is zero (D. J. Mullan 2023, p. 381).

In view of the role that CMEs play in removing helicity from the Sun, I consider it worthwhile in this paper to turn to a consideration of the existence (or absence) of CMEs associated with other stars, especially flare stars.

7. Is There Evidence that CMEs Are Ejected from Flare Stars?

The maximum energy reported in a solar flare is $6 \pm 3 \times 10^{32}$ ergs (G. Kopp et al. 2005). In observations of flares on other stars, the largest energies can exceed the maximum solar flare energy by several orders of magnitude. The numbers of stellar flares which have been discovered in the past 17 yr include more than 800,000 from the Kepler spacecraft (J. R. A. Davenport 2016) and more than 200,000 from the TESS spacecraft (V. Pratt et al. 2026). Among the Kepler flares, J. R. A. Davenport (2016) reported that the average flare

energy is $\sim 10^{35}$ erg, with the distribution extending (among solar-type stars) up to as much as 10^{37} ergs. As already mentioned, the largest solar flares are more likely to be accompanied by CMEs (M. Youssef 2012).

The result of M. Youssef (2012) is often extrapolated to conclude that many stellar flares (especially those with significantly greater energies than the largest solar flares) can safely be assumed to be accompanied by CMEs. Is this assumption supported by any evidence? Turning to the literature, the following responses to this question are instructive.

In the V471 Tauri binary (containing a hot white dwarf plus a K2V flare star), D. J. Mullan et al. (1989) reported the detection (in IUE spectra) of variable discrete lines with outward speeds of order 800 km s^{-1}. They suggested that the wind of V471 Tau "may be dominated by CMEs" ejected by the K2 flare star. In support of this suggestion, note that a K2 dwarf has a radius of 0.783 $R_{\rm Sun}$ and a mass of 0.82 $M_{\rm Sun}$;[1] therefore, the escape speed ($\sim\sqrt{[M/R]}$) from such a star exceeds the solar value by a factor of $\sqrt{[0.82/0.783]} \approx 1.02$,. As a result, $V_{\rm esc}$ (K2) $\approx$ 630 km s^{-1}, and the observed CME speeds of order 800 km s^{-1} exceed V_{esc} by a safe margin. Further support for CMEs in the V471 Tauri system was proposed by H. E. Bond et al. (2001) who used the Hubble Space Telescope to record transient absorptions in the Si III 1206 Å line; it was proposed that these absorptions were created as a CME (containing hot enough gas to lead to twice-ionized Silicon) from the K2 dwarf passed in front of the white dwarf. However, the close binary nature of the system (the separation between the two components is only $\sim$3 times the K star radius) and the high temperature of the white dwarf (with a surface temperature much larger than the K dwarf, and also highly magnetic) make it difficult to draw firm conclusions as regards the possibility of CMEs from single cool dwarfs.

In a landmark paper, E. R. Houdebine (1990, hereafter H90) reported what is perhaps the strongest evidence for a CME from a single M dwarf: the presence of high-speed mass motions in association with a large flare on the star AD Leonis (spectral type M3.5Ve). (Observational evidence that AD Leo is indeed a single star has been provided by speckle interferometry (C. Leinert et al. 1997) and by coronagraphic data (B. R. Oppenheimer et al. 2001).) H90 obtained spectra of AD Leo during and after a large flare: their spectra were centered in the wavelength region of the hydrogen Balmer line Hγ. The data revealed the clear presence of blueshifted components of Hγ having line-of-sight speeds of up to 5800 km s^{-1} in the postflare spectrum. Such speeds are definitely in excess of the escape speed from AD Leo; with a mass of $0.27 M_{\rm Sun}$ and a radius of 0.300 (see footnote [1]), $V_{\rm esc}$(AD Leo) $\sim\sqrt{[0.27/0.300]}$ is less than the solar escape speed by a factor of 0.97. Thus, $V_{\rm esc}$(AD Leo) $\approx$ 600 km s^{-1}. It would have been tempting to claim that an analog of a solar CME had been discovered. Remarkably, however, H90 cautiously remarked "there is no irrefutable evidence that a solar-like CME event was observed." They stated the following principal reason for their caution: "mass ejections have not been previously reported on single M dwarfs."

In the intervening 36 yr since the paper by H90, a great deal of effort has gone into searching for empirical evidence of CMEs in flare stars. A summary of 18 different studies which appeared in print during the years 2014–2025 was provided by C. Tan et al. (2026).

In one of these 18 studies, F. Koller et al. (2021) examined the optical spectra of 630,000 (!) dwarf stars with spectral types F, G, K, and M. CMEs were identified by searching for "asymmetries in the Balmer lines caused by the Doppler effect of plasma motions in the line of sight." Koller et al. discovered less than 300 flares, of which 5 were found to have redshifted asymmetry, while one was found to have blueshifted asymmetry. But none of the six asymmetric candidates showed velocity amplitudes as large as V_{esc}. That is, none could be confidently labeled as a CME.

In another of the 18 studies reported by C. Tan et al. (2026), S.-P. Moschou et al. (2019) reported on a sample of stars which included all candidates currently known at the time of publication as containing some evidence for stellar CMEs. S.-P. Moschou et al. (2019) found that extrapolation of solar data on CME kinetic energies to stellar CMEs produces kinetic energies which are 200 times larger than their analysis of the stellar data yielded.

After evaluating the results in the 18 studies, C. Tan et al. (2026) concluded that "firm observational evidence for stellar CMEs remains very limited." D. Cao & S. Gu (2026) have supported this conclusion by a study of 33 M dwarfs detected in the CARMENES spectral survey; they found 61 flare events with Hα asymmetries, but 60 of the 61 had Doppler shifts less than the escape speed $V_{\rm esc}$, and only 1 event had a shift "approaching" the escape speed.

8. Observational Difficulties in Ejecting and Detecting Stellar CMEs

One theoretical explanation for the paucity of stellar CME detections is that an overlying coronal field B_o (the "strapping field") could impede CME escape (J. D. Alvarado-Gomez et al. 2022). The magnetic tension of the "strapping force" f(str) = $(B_o.\mathrm{grad})B_o\ /4\pi$ (Z. Sun et al. 2026) is directed downward toward the star; the force scales as B_o^2, so a CME could be suppressed if B_o is strong enough. Some M dwarfs are known to have surface fields as large as 7 kilogauss (D. Shulyak et al. 2017), so B_o could be very strong indeed.

A striking example of how difficult it can be to detect even a solar CME spectroscopically was reported by A. G. M. Pietrow et al. (2024, hereafter Pi24) who used imagers to search for CMEs from two X-class flares. One flare image showed a bona fide CME escaping with speed 1910 km s^{-1}, while the second flare image revealed only a nonescaping "pseudo-CME." A separate instrument obtained simultaneous spectra of the "Sun as a star"; surprisingly, neither of the X-class flares showed a Doppler signal. Pi24 concluded that the rareness of spectral evidence for stellar CMEs might be due to "the geometry of the problem."

The age of the star may also be relevant as regards CME detectability. K. Namekata et al. (2025) observed two young flare stars (with ages of 30 Myr and 50–125 Myr) and reported 15 superflares in which an unusually large number ($\approx$27%) exhibited blueshifts with top speeds of 660–1080 km s^{-1}; such speeds do exceed $V_{\rm esc}$, and are plausibly ascribed to CMEs.

The conclusion is that CMEs have been detected in association with some stellar flares, but CMEs have (not yet) been confidently detected in association with most stellar flares. Thus, extrapolation from the properties of solar CMEs to the properties of stellar CMEs is apparently subject to considerable uncertainty.

[1] www.pas.rochester.edu/~emamajek/EEM_dwarf_UBVIJHK_colors_Teff.txt

9. Conserved Magnetic Helicity in a Flare Star Constrains Magnetic Decay

Consider now those flare stars where CMEs are indeed rare. Such stars do not lose their magnetic helicity H_m at any appreciable rate. In other words, $H_m$in those stars (i.e., the integral of $A.B$ over the stellar volume) will retain essentially all of its initial value for periods of time which are much longer than the timescale τ_D on which (unconstrained) magnetic energy characteristically decays. Now, the observational fact that cool dwarfs (including the seven slow rotators highlighted by L24 and B26) are not necessarily completely devoid of flare activity means that the magnetic energy must be decaying to some extent; this is consistent with Taylor's conjecture that H_m may undergo some decay, just so long as it does not decay as fast as magnetic energy does. But the possibility (which is key to the present argument) that H_m (i.e., essentially $A.B$) retains essentially its initial value for times that are much longer than the ohmic dissipation timescale requires that the magnitude of B and the magnitude of A must remain essentially constant on timescales longer than τ_D.

It is noteworthy that L24 reported on data which they obtained over two or three observing seasons for each star. As a result, there are 17 separate data points shown in Figure 19 of L24, which displays mean field strength versus Rossby number. The multiple results for any one star (in their sample of six) are all plotted in their Figure 19 as open red circles arranged vertically at a single value of Ro; this shows clearly that the magnitude of the stellar magnetic field strength varies from one observing season to another, i.e., between 2019 October and June 2022, although the value of Ro, i.e., the rotational period, (not surprisingly) does not exhibit any detectable change from 2019 to 2022. The changes in field strength from season to season can be read by visual inspection of Figure 19 in L24; the fields for each of the six stars are found to range (in units of Gauss) from 100 to 200, from 40 to 80, from 70 to 160, from 80 to 100, from 25 to 60, and from 100 to 150. As for YZ Ceti (see B26), which has a Ro value overlapping with the range of Ro values in the L24 sample, the field strength was reported to be as strong as 276 G.

It is striking to examine Figure 19 of L24 to determine the field strengths which have been detected in "normal" (weak-field) stars whose Ro numbers lie in the same range of Ro as the six stars in the L24 sample. For these "normal" stars, visual inspection of Figure 19 in L24 indicates that the field strengths have magnitudes of as little as 0.5 G, and no more than 5 G. Thus, stars with equal values of Ro can have field strengths which differ by a factor as large as 400 (or as large as 550 when we include YZ Ceti).

The seven stars in the L24 sample plus YZ Ceti are stars with fields which are stronger than other stars with identical rotational properties. In the context of the results of J. D. Alvarado-Gomez et al. (2022), the conclusion could be that the six stars in the L24 sample (as well as YZ Ceti) have stronger "strapping" fields in their atmosphere than in other stars with identical rotational properties. Stronger strapping fields would ensure that CMEs are more likely to be suppressed. Therefore, the results of J. D. Alvarado-Gomez et al. (2022) suggest that the seven stars in the L24 and B26 samples are less likely to experience CMEs. In such a case, the six stars in the L24 sample (as well as YZ Ceti) have less chance to eject magnetic helicity. As a result of retaining larger magnetic helicity, these seven stars are more constrained by the Taylor conjecture, and their magnetic energy has not been permitted to decay at the "expected" rate. The fact that these seven stars retain strong fields means that the combination of wind outflow from each star and its strong magnetic field supplies an effective mechanism for braking the star's rotation (E. J. Weber & L. Davis 1967).

The hypothesis in this paper is that two classes of stars can be identified in Figure 19 of L24. Class 1, plotted as open red circles in L24, represent slowly rotating stars with strong large-scale (strapping) fields. This class also includes the star YZ Ceti (B26). In such stars, CMEs with energies that lie below a threshold are prevented from escaping from the star. Class 2, plotted as the filled symbols (stars, diamonds) in Figure 19 of L24 are stars with the same Ro values as the six open red circle stars (i.e., equally slowly rotating stars), which have strapping fields that are weaker than those in Class 1 stars by factors of up to 400–550. Recalling that the strapping force which impedes CME escape scales as the square of the magnetic field strength (see Section 8), the impeding (strapping) force on a CME in Class 2 stars is weaker than the impeding force on a CME in Class 1 stars by factors of up to 160,000–300,000.

As a result, stars in Class 2 are expected to be stars in which CMEs are permitted to escape. In view of this, I suggest that the stars represented as filled diamonds and stars in the lower right-hand corner of Figure 1 of L24 could be more favorable candidates to search for stellar CMEs.

10. Conclusion

Large amounts of effort have been expended in recent years into searching for CMEs from flare stars. But despite the detection of more than 10^6 stellar flares by satellites in the past 17 yr, the results of the many searches for CMEs have been disappointing, with so far no more than 10–15 confident detections (S.-P. Moschou et al. 2019). As C. Tan et al. (2026) have remarked, "firm observational evidence for stellar CMEs remains very limited." It is true that several reasons can be identified as to why stellar CMEs are difficult to detect (see Section 8). Despite these difficulties, I consider it worthwhile to explore the consequences of the possibility that certain flare stars do not always emit CMEs in association with their flares.

In the case of the Sun, tens of thousands of CMEs have been detected in the course of the past few solar cycles. As a result, many physical features of CMEs have been extensively studied. One particular feature of CMEs is relevant here: CMEs serve to remove from the Sun a physical quantity known as magnetic helicity (defined in Section 5 above). In view of the disappointingly few reports of stellar CMEs, it appears that (at least some) flare stars may not be as effective as the Sun in losing magnetic helicity.

In the context of MHD turbulence in a medium, certain physical variables are known to be strictly conserved if the medium is "ideal," i.e., has infinite electrical conductivity. But even in a nonideal medium, where there exists finite resistivity, certain "rugged invariants" (including magnetic energy and magnetic helicity) are expected to be "almost" conserved. For present purposes, the essential aspect of these invariants is known as the Taylor conjecture: magnetic helicity must decay more slowly than magnetic energy. As a result, a serious constraint is imposed on how fast magnetic energy is allowed to decay if, at the same time, the helicity is forced (by some means) to remain essentially constant.

In view of such a possibility, in a star which emits no (or few) CMEs, the constraint imposed by the Taylor conjecture

leads to a pronounced reduction in the rate at which magnetic energy may be removed from that star. As a result, observations of a star which is a slow rotator at the present time may lead to the detection of field strengths which are not representative of what the star is capable of generating at the present time. Instead, the detected fields would be essentially remnants "frozen in" from an earlier epoch when the star used to rotate more rapidly, and could therefore have relied (in that earlier epoch) on dynamo operation to generate stronger fields.

I suggest that stars which are undergoing the constraints of the Taylor conjecture are candidates to explain the existence of a certain group of seven interesting stars which have been identified by L24 and by B26, namely, slowly rotating M dwarf stars which have unusually strong large-scale fields (20–276 G). I also suggest that stars with similar rotational speeds but weaker large-scale magnetic fields would be good candidates to observe in search of stellar CMEs.

Although I have in this paper focused on processes which control how cool dwarfs lose their fields, this does not imply that the processes by which cool dwarfs acquire their fields are not also relevant to the problem at hand. An anonymous referee has stressed that the "process through which stars acquire magnetic fields would still be worth understanding." If, as I claim in this paper, the seven "interesting" stars in L24 and B26 do indeed have stronger strapping fields than other stars with similar Ro numbers, this could be due to stronger dynamos which operated in the past in the "interesting" stars. In any particular star, the field which it eventually possesses at any particular moment in its development involves a complicated interaction between acquiring and losing a field. I have chosen to focus mainly on field loss in cool dwarfs in the present paper.

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