The M4 Transition: Toward a comprehensive understanding of the transition into the fully convective regime

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Abstract. The difference in stellar structure above and below spectral type \textasciitildeM4 is expected to be a very important one, connected directly or indirectly to a variety of observational phenomena in cool stars—such as rotation, activity, magnetic field generation and topology, timescales for evolution of these, and even the basic mass-radius relationship. In this Cool Stars XVI Splinter Session, we aimed to use the M4 transition as an opportunity for discussion about the interiors of low-mass stars and the mechanisms which determine their fundamental properties. By the conclusion of the session, several key points were elucidated. Although M dwarfs exhibit significant changes across the fully convective boundary, this “M4 transition” is not observationally sharp or discrete. Instead, the properties of M dwarfs (radius, effective temperature, rotation, activity lifetime, magnetic field strength and topology) show smooth changes across M3–M6 spectral types. In addition, a wide range of stellar masses share similar spectral types around the fully convective transition. There appears to be a second transition at M6–M8 spectral types, below which there exists a clear dichotomy of magnetic field topologies. Finally, we used the information and ideas presented in the session to construct a framework for how the structure of an M dwarf star, born with specific mass and chemical composition, responds to the presence of its magnetic field, itself driven by a feedback process that links the star’s rotation, interior structure, and field topology.
1. Introduction

The interior structure of a star is a function of its mass. Above a threshold mass of $\sim 0.3 \, M_\odot$, the interior is expected to resemble that of the Sun, having a radiative zone and a convective envelope. In contrast, below the threshold mass the convection zone extends all the way to the core.

Despite not having a strong radiative/convective interface (like that found in the Sun), mid- to late-type M dwarfs (spectral type of M4 and greater) are observed to have strong magnetic fields and subsequent surface heating that results in observed magnetic activity (traced by strong line or continuum emission). Recent theoretical modeling of stars with convective envelopes that extend to the core (and a lack of a strong radiative/convective interface) were able to produce strong, long lived, large scale magnetic fields (Browning 2008). Observational results also suggest that in mid- to late-type M dwarfs, the fraction of the magnetic field in large scale components is larger than in early type M dwarfs (Donati et al. 2008; Reiners & Basri 2008).

These are just some examples of the phenomena and questions that play out around the M4 spectral type. The purpose of this Cool Stars XVI Splinter Session was to use this specific transition point—the M4 transition—as an opportunity for focused discussion and "out of the box" collective thinking about the interiors of low-mass stars, what we know, what we don’t know, what we wish we understood better. We intended this to be a rich, fun session to bring together observational evidence from multiple directions with the goal of disentangling the effects of multiple physical phenomena and leading toward a clearer set of guiding questions for future work.

2. The M4 transition

Neill Reid began by reminding us of some of the basic properties of M dwarfs and of the basic predictions of theoretical stellar evolution models for M dwarf interior structure. Most theoretical stellar evolution models predict the transition into the fully convective regime to occur at a stellar mass of $\sim 0.3 \, M_\odot$, but differ in detail. For example, Chabrier & Baraffe (1997) predict the boundary to occur at $M \approx 0.35 \, M_\odot$ (spectral type M2), whereas Dorman et al. (1989) place the fully convective boundary at $M \approx 0.25 \, M_\odot$ (spectral type M4). For the fiducial properties of M2 stars, refer to the benchmark systems Gliese 22A (Henry & McCarthy 1993) and Gliese 411 (Lane et al. 2001), both with empirical masses of $\approx 0.36 \, M_\odot$ and the latter with an interferometrically measured radius. For the fiducial properties of M4 stars, refer to the benchmark eclipsing binary CM Dra, comprising two M4.5 stars with masses of 0.22 $M_\odot$ (e.g. Morales et al. 2009).

Table 1 gives a summary of the physical properties of spectral type M2 and M4.5 stars.

| Name   | Mass ($M_\odot$) | Radius ($R_\odot$) | $T_{\text{eff}}$ | $M_V$   | $V-K$   |
|--------|-----------------|--------------------|-----------------|---------|---------|
| GJ 22 A | 0.352 ± 0.036   | ...                | 3380 ± 150      | 10.99 ± 0.06 | 4.55 |
| GJ 411  | 0.403 ± 0.020   | 0.393 ± 0.008      | 3828 ± 100      | 8.08 ± 0.09 | 4.25 |
| CM Dra A | 0.2310 ± 0.0009 | 0.2534 ± 0.0019   | 3130 ± 70       | 12.78 ± 0.05 | 5.10 |
| CM Dra B | 0.2141 ± 0.0010 | 0.2396 ± 0.0015   | 3120 ± 70       | 12.91 ± 0.05 | 5.10 |
2.1. Basic stellar properties

Neill Reid discussed the observed properties of M dwarfs across the fully convective boundary. It is useful to recall up front that certain fundamental stellar properties do not evince any obvious manifestation of the changes in stellar structure that accompany the transition into the fully convective regime. For example, the mass-luminosity relation is smooth through the M spectral types. Similarly, Figure 1a shows the radius-luminosity relation for a large sample of M dwarfs (Ribas 2006; Demory et al. 2009): The observed radius-luminosity relation is smooth through the M spectral types, as predicted by stellar evolution models. Evidently, energy generation and output in these stars does not much know or care about changes in structure or in energy transport that may be occurring across the fully convective boundary.

Figure 1. Left: Radius-luminosity relation for M dwarfs. Crosses are nearby field M dwarfs with reliable parallaxes, and temperatures derived from $V-I$ colors. The relationship is smooth across the M spectral types, as predicted by stellar evolution models (dashed lines). Right: Radius-$T_{\text{eff}}$ relation. As highlighted Clemens et al. (1998), there is a marked decrease in radius near spectral type M4. Note, however, that this change in the radius-$T_{\text{eff}}$ relationship is not infinitely sharp, but rather is a finite transition from spectral types M3 to M6.

However, other basic stellar properties do manifest clear changes across a mass of $\sim 0.3 \, M_\odot$. Figure 1b shows the radius-temperature relation for the same stars in Figure 1a. Unlike the featureless radius-luminosity relation, here we see a clear change in slope—with the stellar radii decreasing rapidly with decreasing effective temperature—centered around $T_{\text{eff}} \sim 3150$ K (spectral type M4). The change in stellar radius here is a factor of $\sim 2$. In other words, there is a relatively large range of stellar mass and radius over a relatively small range of spectral types. Indeed, stars with a wide range of masses around the fully convective transition are predicted to have similar spectral types (cf. Fig. 4 in Chabrier & Baraffe 2000), a consequence of the flatness of the mass-temperature relation caused by H$_2$ formation. There is a strong morphological similarity between the observed and predicted relations, but the two are offset by $\sim 250$K, with the observations cooler than the models (compare pink and black curves in Fig. 1).

Notably, the change in the radius-temperature relation near M4 is not an abrupt step function; rather, it is a finite transition between $T_{\text{eff}} \approx 3300$ K and $T_{\text{eff}} \approx 2850$ K.
(i.e. spectral types M3 to M6). At later spectral types, the stellar radii asymptotically approach the value of \( \approx 0.1 R_\odot \) dictated by electron degeneracy pressure.

As Leslie Hebb discussed, recent direct radius measurements of M dwarfs in eclipsing binaries show the stellar radii to be inflated relative to the radii predicted by theoretical stellar evolution models (e.g. Ribas 2006). This has been attributed to the effects of stellar magnetic fields and activity (e.g. Morales et al. 2008). The magnitude of this effect does change across the fully convective boundary (Figure 2), but as above it does not appear to change in an abrupt fashion.

![Figure 2](image1.png)

**Figure 2.** *Left:* Mass-radius relation for eclipsing binary systems with masses and radii measured to better than 3%. *Right:* Fractional increase in the radii over the theoretically predicted radii (Baraffe et al. 1998). The enlarged radii are thought to be caused by the effects of magnetic fields. Early type M dwarfs show a larger increase in radii compared to late-type, fully convective M dwarfs, consistent with predictions of theoretical models (Mullan & MacDonald 2001; Chabrier et al. 2007).

### 2.2. Stellar activity and stellar rotation: Effects of stellar age

As Jonathan Irwin and Richard Jackson discussed, recent observational results have confirmed that the M4 transition plays an important part in shaping the rotation and magnetic activity evolution of M dwarfs. Large samples of M dwarfs show an increase in activity fractions around spectral types of \( \sim M4 \) (West et al. 2008).

![Figure 3](image2.png)

**Figure 3.** Activity lifetime as a function of spectral type for M dwarfs (West et al. 2008). The lifetime over which an M dwarf stays active is a strong function of spectral type, from 1–2 Gyr for M3 dwarfs to 7–8 Gyr for M6 dwarfs. Evidently, activity lifetime does respond to the change in internal structure across the fully convective boundary, but the transition is a finite one between M3 and M6.
This result has been shown to be dependent on the ages of the stars. When looking at the activity fractions as a function of the M dwarfs’ location above the Galactic plane, and using a simple model of dynamical heating which scatters M dwarfs to larger Galactic scale heights over time, [West et al. (2008)] determine the amount of time that M dwarfs of different spectral types remain chromospherically active. They find that the “activity lifetime” changes dramatically between spectral types M3 and M6 (from 1–2 Gyr for M3 dwarfs to 7–8 Gyr for M6 dwarfs; Fig.3).

This important transition was bolstered by the rotation analysis of [Reiners & Basri (2008)], who found that the average rotation velocities of a nearby sample of M dwarfs increases dramatically and monotonically as one looks at later spectral types. The average $v \sin i$ is <3 km/s at M2, increases to ~10 km/s at M6, and continues increasing to ~30 km/s at L4 (Figure 4). This almost certainly points to a lengthening of the timescale for stellar spindown as the stellar structure changes from solar-type (i.e. radiative core + convective envelope) to fully convective. However, the transition is not a step function, thus again pointing to the importance of evolution over time.

The importance of time evolution is seen most clearly in rotation-period distributions in populations of different ages. Fig. 5 shows the evolution of stellar rotation periods from ~1 Myr to $\gtrsim$10 Gyr. The situation among the pre–main-sequence populations is complex, likely due to the effects of multiple competing phenomena (Bouvier 2009). However, at ages of ~100 Myr and older, the stars show a clear pattern with two dominant sequences of rapid and slow rotators; the slow-rotator sequence becomes increasingly dominant with increasing stellar age. These are the so-called ‘C’ and ‘I’ sequences of the Barnes “gyrochronology” paradigm (Barnes 2003, 2007).

Importantly, it is also clear from this figure that at all ages there is a spread of stellar rotation periods near the fully convective boundary; age alone does not determine whether a given M4 star will be on the ‘C’ sequence or on the ‘I’ sequence. Thus, while all stars appear to follow a similar pattern of evolution in stellar rotation, presumably connected to evolution of their interior structure and magnetic field properties, there is evidently star-to-star scatter in these properties at any given age.

2.3. Magnetic fields: Topology and effects on stellar properties

As discussed by Moira Jardine and Julien Morin, M dwarfs also show clear topological changes in their surface magnetic fields as a function of spectral type. Figure 6 shows...
Figure 5. Observed rotation period distributions for low-mass stars in clusters of varying ages. Among clusters with ages >100 Myr, two sequences of rapid and slow rotators are observed, with the slow-rotator branch becoming increasingly dominant with time. At the fully convective boundary (vertical line), the stars do not transition to the slow-rotator sequence instantaneously, but rather on a finite timescale.

A simple cartoon illustration summarizing the basic change that is observed: from globally weak but highly structured (i.e. multipolar and non-axisymmetric) fields at early spectral types, to globally strong and well ordered (i.e. dipolar) fields at later spectral types. In other words, the energy in the dipole component, relative to higher-order components, is higher in the lower-mass stars. Figure 6b depicts these changes in reference to three specific low-mass stars (Gl 494, EV Lac, EQ Peg b) whose magnetic field topologies have been modeled in detail (Jardine et al. 2002) using Zeeman Doppler Imaging (ZDI) maps as boundary conditions (Donati et al. 2008; Morin et al. 2008). This is shown more quantitatively in Figure 7, which depicts the field topology and strength as a function of stellar mass, derived for a large number of low mass stars using the ZDI technique. Interestingly, we see a hint of two transitions here. The first occurs near the fully convective boundary, where as already mentioned the fields transition from a globally weak, highly structured topology, to a globally strong, dipolar topology. A second transition appears at spectral type M6–M8, such that below M ∼ 0.15 M⊙, stars with similar stellar masses and rotational properties can have very different magnetic topologies. This apparent M6–M8 transition could be reflecting the point at which the stellar atmospheres become completely neutral (e.g. Mohanty & Basri 2003), though it could again reflect an age effect as witnessed in the bifurcated rotational properties of M dwarfs (see Fig. 5).

Finally, it is important to bear in mind that the ZDI measurements, because they rely upon observations of polarized light, are probing field components that represent only a few percent of the total magnetic energy. There is likely a large amount of magnetic flux in small-scale field components (which do not contribute much net polarized light) in addition to the larger scale components that the ZDI technique is mapping.
Dermott Mullan discussed recent modeling efforts to account for the observed inflated radii of M dwarfs compared to the predictions of most (non-magnetic) theoretical stellar evolution models. Chabrier and collaborators have suggested that strong surface fields can inhibit surface convection and also create cool starspots, both of which act to decrease the surface temperature and then—because the stellar luminosity generated in the core is unaffected—requires an increase in the stellar radius.

Mullan also discussed alternate models in which a strong field threads the entire star. These models can successfully reproduce for example the observed temperature reversal in the brown-dwarf eclipsing binary 2M0535–05 (Figure 8), which at an age of only $\sim$1 Myr has a spectral type of M6. These models do predict a change in the stellar luminosity as a result of the very strong ($\sim$MG) fields in the core (Figure 9).

### 3. Putting it all together: A conceptual framework

Figure 10 is an initial attempt to conceptually summarize the inter-related phenomena discussed during our Session. This is not intended to be inclusive of all mechanisms or observable phenomena possibly relevant to M dwarfs, and it is by necessity a simplified representation of what is likely to be a more complex set of inter-relationships.

The figure attempts to represent the complex set of causal relationships—stellar structure, magnetic field topology, rotation, magnetic field strength—that mediate the fundamental relationships between basic stellar properties (e.g., how mass and composition ultimately translate into radius and effective temperature). As depicted in the figure, we imagine that, absent any magnetic field effects, there would be a single, fundamental mass–radius–temperature relationship (modulo metallicity). This relationship is, however, modified by the presence of a magnetic field that manifests itself on the surface through various activity tracers (e.g. chromospheric Hα emission). This magnetic field affects the observed surface properties of the star (effective temperature and radius) via surface effects (i.e. star spots; Chabrier et al. [2007]) and/or via a strong field that inhibits convection throughout the stellar interior (Mullan & MacDonald [2001]).

The mechanism that drives the magnetic field's action (and perhaps its generation) is likely complex, but almost certainly involves at its heart a rotational dynamo. We
envison that the star’s rotation directly affects the strength of the magnetic field (more rapid rotation → stronger field) for stars below the saturation threshold. In general, a stronger field will drive a more rapid evolution of the star’s angular momentum, leading to a decline of the star’s rotation on a certain spindown timescale, and this spindown in turn feeds back into the strength of the field, dialing it down over time.
The M4 Transition

Figure 8. The reversal of effective temperature with mass for the brown-dwarf eclipsing binary 2M0535–05 (Stassun et al. 2006, 2007) can be explained by recent models that include the effects of strong magnetic fields threading through the entire interior of a low-mass star (MacDonald & Mullan 2009). Solid curves show the non-magnetic models for the primary (more massive) brown dwarf (red) and the secondary brown dwarf (blue), dashed lines show the magnetic models.

Importantly, the magnetic field acts according to an intricate feedback process such that the magnetic field impacts the stellar structure (i.e., convection zone depth) and rotation rate of the star which in turn affects the (re)generation of the field. The nature of the dynamo itself depends on the interior structure (i.e., convection zone depth). As the star approaches a more fully convective state (that is, as the size of the radiative zone recedes), there must be a transition from a solar-type ($\alpha - \omega$) dominated dynamo to a purely turbulent ($\alpha^2$) dynamo. The spindown timescale is probably intimately coupled to the field topology, but exactly how the two are connected is not obvious. For example, later type M dwarfs have longer spindown timescales, yet these same stars have magnetic field topologies which possess more open field lines (i.e. dipolar fields), which would seem to enable them to more effectively drive mass and angular momentum loss. Clearly, we do not yet understand entirely how magnetic topology affects the observed rotational evolution of these stars.

It is moreover not clear whether the dynamo-driven strength of the field can feed back into the depth of the convection zone and/or the field topology. For example, it is thought that a very strong field can cause an otherwise fully convective star to generate a radiative core, either directly through the inhibition of convection at the center of the star (e.g. Mullan & MacDonald 2001) and/or indirectly through altering the boundary conditions at the stellar surface (e.g. Chabrier et al. 2007). Similarly, in some models very rapid stellar rotation can cause the opening of surface field lines (e.g. Jardine et al. 2010). Thus, the inter-relationships between rotation, field strength, interior structure, and surface field topology are likely complex, non-linear, and in any event dependent on the age of the star through its rotational history.

The rotation-period distributions of low-mass stars as a function of stellar age show that rotation is not simply a function of time alone. Indeed, current thinking identifies
at least two dominant sequences of rotational properties in clusters (e.g., the ‘C’ and ‘I’ sequences of Barnes), such that a star of a given mass and age is likely to have one of two possible rotation periods. Perhaps these distinct rotational sequences reflect stars in different states of the complex feedback mechanisms between field generation, dynamo type, and field topology explored above. Indeed, the ZDI maps of field topologies appear to bear out this picture of multiple types of field configurations intermixed among the M3–M6 spectral types (Figure 7). Given this, and in light of the time-dependence of these effects, it is perhaps not surprising that the “M4 transition” across the fully convective boundary is not a sharp transition, but rather “smeared” from approximately M3 to M6. For example, the two eclipsing binaries CM Dra and CU Cnc (see Fig. 1), with masses and radii that differ by a factor of ~2 but with nearly identical effective temperatures (spectral types ≈M4), may be exemplars of this smearing effect.

4. Open questions and future work

We concluded with an open discussion leading to a set of questions to help guide ongoing work by the community interested in the “M4 transition” and related phenomena.

1. What field strengths are necessary and reasonable in the interiors of stars to potentially explain the observed mass-radius relationship?

2. Abundance measurements needed! (e.g. [O/Fe]) The mass-radius relationship is actually a mass-radius-abundance relationship. FGK+M binaries are a promising approach, tying M dwarf abundances to FGK primary stars.
The M4 Transition

Figure 10. Representation of the process by which magnetic fields influence the interior structure and observed fundamental properties of M dwarf stars. M dwarfs are defined intrinsically by mass and chemical composition which determine the initial depth of the convection zone. This in turn affects the magnetic field topology and strength through the dynamo type (α–Ω or α²). The rotation rate, which is moderated by angular momentum loss through stellar winds determined largely by the field topology, in turn affects the field strength for stars in the non-saturated regime via the dynamo process. X-rays, chromospheric emission, starspots, and flaring all trace the magnetic activity. Over time, stars spin down and the magnetic field weakens, causing the entire system to evolve. It remains unclear how much feedback there is in the system. Does the strength of the magnetic field affect the topology or the convection zone depth, and how much does the rotation rate influence the field topology? Taken together, the interlinked magnetic fields, internal structure, and rotation properties affect the resulting fundamental parameters: radius and temperature. However, the detailed mechanism by which the latter occurs is not yet fully understood.

3. Continue to identify low-mass eclipsing binaries. Long-period systems are needed to disentangle effects of magnetic activity on stellar radii and temperatures.

4. Examine selection effects in samples, especially with regard to activity. Ages of stellar samples matters.

5. What is the mass of the fully convective boundary? Depends on rotation/activity/age?

6. Other observational clues: Period gap in CVs (2–3 hr periods) → kink in mass-radius relationship?

7. Independent radius measurements: interferometry, \( P_\text{rot} + v \sin i \) (gives \( R \sin i \))
8. Bulk of field is in very small-scale structures → How to fully characterize the fields? Constraints from many techniques/tracers are needed to fully characterize magnetic fields: Zeeman broadening, spectropolarimetry, radio, X-rays, etc.

9. “M6–M8 transition” in field topologies, caused by neutral atmospheres? Age?

10. How does the fully- to partly-convective evolution on the pre–main-sequence affect the early magnetic and rotational history of low-mass stars?

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