Understanding Activity in Low–Mass Stars

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1. Introduction: the Challenge of Low-Mass Star Activity

Low-mass stars make up the majority of stellar constituents (∼75% by number) in the Galaxy. These stars are smaller, less massive and considerably less luminous than the Sun, yet they allow for a statistical probe of the structure, evolution and dynamics of the Milky Way, as well as an important glimpse into the structure of stars. As the most common of potential planetary hosts, cool stars are also increasingly popular targets for planet hunters and may end up being an important population for astrobiology. Despite their cool effective temperatures and largely neutral photospheres, low-mass stars have strong magnetic dynamos. Non-radiative heating processes transfer energy from the magnetic field into the stellar atmosphere, powering both steady-state emission from X-rays to radio, as well as energetic flares that contribute to the transient population and affect the habitability of orbiting planets. Although this magnetic heating (or activity) has been observed for decades, the exact mechanisms that control magnetic activity in M dwarfs are still not well-understood. **In this white paper, we ask two broad questions regarding activity in low-mass stars: 1) How do the observable magnetic fields depend on fundamental stellar parameters like mass, age, and rotation rate? and 2) What physical processes govern field generation?**

The next decade may bring fundamental changes in our understanding of magnetic activity at the bottom of the Main Sequence. Historically, studies of these intrinsically faint low-mass stars have been limited to small samples of nearby objects. However, major advancements in the last several years have laid the foundation for the coming pivotal decade. Novel observational techniques, such as spectropolarimetric Doppler imaging of the magnetic field distribution are providing new windows into stellar activity. Bigger, more sensitive telescopes will allow us to push investigations to lower mass, fainter objects at larger distances than currently possible. The advent of large-scale time domain surveys will provide an additional dimension to future observations, allowing the characterization of activity on all timescales. New theoretical advances in understanding dynamos will be possible, driven partly by increasing computational power. In the next decade, the largest supercomputers will routinely attain speeds in the Petaflop range – giving the theoretical community an unprecedented opportunity to model the physics of magnetic activity with greater fidelity. In the following sections, we briefly discuss the present state of our understanding, and highlight how these advancements may be best used to proceed in the upcoming decade.

2. Manifestations of Magnetic Activity: Tracing Fields Directly and by Proxy

Magnetic activity in low-mass stars can be traced by a number of observables across the electromagnetic spectrum. While some of these tracers are secondary effects of the magnetic field (e.g. emission lines produced by the heating of the upper atmosphere), a few manifestations are direct probes of the field. Understanding how these tracers change as a function of mass, rotation speed, age and metallicity is of vital importance to constraining dynamo models and modeling the retention of planetary atmospheres. In this section, we discuss the current state of magnetic activity observations in low-mass stars and identify specific questions that remain unanswered.

2.1 Activity Across the Electromagnetic Spectrum

The manifestation of magnetic activity is a strong function of spectral type (or equivalently mass/temperature) and age. In the Sun, chromospheric activity is typically traced by observations of the bright Ca II lines emission lines. On M dwarfs, high surface gravity compresses the stellar atmosphere, leading to particularly strong Balmer emission (Linsky 1982). This fact, combined with the intrinsic faintness of M dwarfs in the blue, has made the red Hα line the primary diagnostic spectral feature of chromospheric activity. The subset of these stars which also show Hα emission are designated "active" (dMe). In addition to Hα, many M dwarfs have strong continuum emission in the radio and X-ray, as well as prominent lines of singly ionized metals, particularly the Ca II H and K resonance lines in the blue, and lines of Mg II and Fe II in the UV.

Spectral type and age conspire to affect statistical observations of activity in low mass stars. For example, the fraction of active low-mass stars (as traced by Hα emission) changes as a function of spectral type. Early-type M dwarfs and most of the L dwarfs are rarely active (a few percent in the field) but mid to late-type M dwarfs can be very active; the activity fraction peaks around a spectral type of M7 (70%; Joy & Abt 1974; Reid, Hawley & Gizis 1995; Hawley, Gizis & Reid 1996; Gizis et al. 2000; West et al. 2004) . While the active fraction of M dwarfs can be attributed to an age effect (early-type M dwarfs have shorter active lifetimes than late-type M dwarfs; West et al. 2008), the fall in activity fraction after M7-8 has been attributed to the rise of neutral atmospheres in late-M/early-L dwarfs. However, the small number of high quality L dwarf optical spectra puts severe limits on the empirical activity relations. SDSS observed over 600 L dwarfs (400 new) but the quality of most of the spectra does not allow for a detailed activity analysis. *A deep spectroscopic survey that includes at least 1000 late-M/early-L dwarfs is required to properly assess the presence and level of activity in the coolest stars.*

The strength of activity (as characterized by the ratio of luminosity being emitted in Hα to the bolometric luminosity) also varies as a function of spectral type. The mean $L_{H\alpha}/L_{bol}$ remains constant at around 0.01% from M0-M5, whereafter it drops by an order of magnitude by the early L-dwarfs and another order of magnitude by the late L dwarfs (Burgasser et al. 2002; Cruz & Reid 2002; West et al. 2004). In addition, there is a spread in the mean $L_{H\alpha}/L_{bol}$ relation of half an order of magnitude, which cannot be explained by an age-activity relation alone (West et al. 2009). Instead the spread likely represents a spread in the intrinsic activity of M dwarfs (or in individual stars). Multi-epoch spectral observations of active M dwarfs would help decipher between a spread of activity in the M dwarf population and the variation on a single star. Limited data exist from radial velocity searches around low-mass dwarfs (see Walkowicz & Hawley 2009), but are limited to a small volume that is biased toward younger ages and higher levels of activity. *There are currently no data available to study how activity variations in individual stars varies as a function of age.*

The active fractions, active lifetimes and level of activity for tracers other than Hα are not as well constrained. Studies of X-ray, UV and radio emission from active low-mass stars reveal that a large amount of energy is released at non-optical wavelengths (e.g. Covey et al. 2008; Walkowicz et al. 2008; Berger 2006). However, the small sample sizes and shallow volumes limit our ability to understand the prevalence and duration of non-optical radiation. While all of the activity-induced emission aids in constraining models of dynamo generation and atmospheric heating, the radio emission provides a direct measurement of the magnetic field (see §2.4). Understanding the conditions that give rise to high energy emission (X-ray and EUV) in low-mass stars is particularly important for low-mass stars that host planets, where long duration exposure to high energy photons may significantly affect the atmospheres and habitability of close-orbiting worlds. *Future non-optical surveys (in particular at X-ray and UV wavelengths) that probe low-level emission out to 300 pc will include a sufficient number of low-mass stars and the necessary diversity of ages required to assess the duration and evolution of activity at these wavelengths.*

2.2 The Rotation-Activity Connection

Observations of magnetism in Sun-like stars have established that there is a striking correlation between rotation and stellar activity (e.g., Noyes et al. 1984; see Figure 1). Across a broad range of stellar masses, magnetic field proxies like chromospheric and coronal emission increase in intensity with increasing rotational velocity, then “saturate” at a threshold velocity that depends upon stellar mass (e.g., Pizzolato et al. 2003). Remarkably, several studies have found evidence that some form of rotation-activity correlation persists into the fully convective regime (e.g., Delfosse et al. 1998; Mohanty & Basri 2003; Reiners & Basri 2007; Reiners, Basri & Browning 2009), despite the qualitatively different dynamo believed to operate in such stars (see §3). But measuring the rotation rates of M-dwarfs in the “unsaturated” part of the rotation-activity correlation is very difficult, because rotational velocities in that regime generally correspond to $v\sin i$ that are not currently detectable by Doppler broadening measurements. *It is therefore unclear whether activity in fully convective stars increases gradually with rotation rate, or instead changes more suddenly than in Sun-like stars.* Further complicating this picture are recent findings that the close correlation between rotation and activity may break down at somewhat lower masses (West & Basri 2009). The study of such correlations has been complicated by the fact that most of the low-mass stars that can be spectroscopically observed at high-resolution (in particular late-type M dwarfs) are nearby, and therefore younger (and more active) than more distant populations

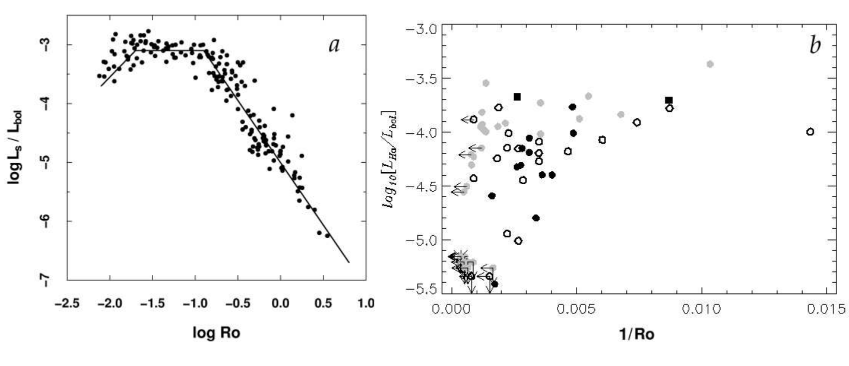

Figure 1: Observations of rotation-activity correlations in (*a*) main-sequence stars at a range of spectral types and (*b*) M-type dwarfs. (*a*) X-ray activity as a function of Rossby number, showing linear, saturation, and super-saturation regimes (from Feigelson et al. 2003; *b*) Chromospheric activity with inverse Rossby number for M4.5-M8.5 dwarfs, with M4-M5 dwarfs grey, M5.5-M6.5 dwarfs as black open circles, and M7.5-M8.5 stars shown as black filled symbols (from Mohanty & Basri 2003)

Correlations of rotation and activity also imply correlations between age and activity, as stars spin down with age (due to angular momentum loss via a magnetized stellar wind). Indeed, such correlations have been observed for decades in low-mass dwarfs (Eggen 1990; Stauffer et al. 1994; Fleming et al. 1995; Hawley et al. 2000; Gizis et al. 2002). Using over 40,000 SDSS spectra and a 1D dynamical model, West et al. (2008) derived the Hα activity lifetimes for M0-M7 dwarfs, finding that early-type M dwarfs have active lifetimes of 1-2 Gyr, while late-type M dwarfs have active lifetimes that exceed 7 Gyr. This striking difference in age reflects the transition from a two-layer radiative-convective interior to one that is fully convective (see §3). Recently, West et al. (2009) showed that the level of Hα activity decreases as a function of time and derived quantitative relations between the level of activity and the age of the low-mass star.

There is reason to believe that activity traced at other wavelengths also declines with age, but that the timescale may be different from that of Hα (Walkowicz & Hawley 2009; Garces et al. in prep). As discussed above, understanding the age-activity relations for the highest energy activity tracers (e.g. X-ray and EUV) is vital to determining incident radiation on planets in orbit around low-mass dwarfs. *We reiterate the importance of UV and X-ray surveys that span a large range in age and include enough low-mass stars for meaningful statistical analysis (∼1000 stars).*

2.3 Magnetic Activity in the Time Domain

In addition to the *quiescent* magnetic activity (persistent chromospheric and coronal emission in the optical, UV and X-ray) that has been discussed above, many low-mass dwarfs also produce large flare events. Flares are manifestations of internal magnetic field production and the subsequent emergence of these fields at the stellar surface. Although many studies of individual flares exist, there are few statistical studies of flare rates (Lacy et al. 1976, Audard et al. 2000, Welsh et al. 2007). For many years, the only study in the optical was Lacy et al. (1976), which was limited to observations of eight of the most active, well-known flaring M dwarfs. Little is known about the flare rate of somewhat less active M dwarfs, nor about how the flare frequency and energy changes with spectral type and age.

Recent results from SDSS repeat photometry (Kowalski et al. 2009) provided a somewhat less biased sample. Of the SDSS stars that have spectra and which also show flares in the SDSS photometry, 92% have Hα in emission during quiescence. However, not all stars that flared in SDSS had Hα in emission– 8 *inactive* stars in the sample flared as well. Therefore, while cool stars are designated as "active" only if they have Hα in emission, most so-called "inactive" stars actually possess low to moderate levels of magnetic activity and therefore also flare. Future large–scale time–domain surveys will improve upon the SDSS results by providing all-sky observations with a long time baseline. The improved depth of these surveys will particularly improve statistics for intrinsically faint ultracool dwarfs. The spatial flare rate (number of flares/hour/sq deg) is a metric of interest for such surveys– despite being astrophysically interesting in–and–of themselves, stellar flares also constitute a variable foreground "fog" that confuses the identification of "true" transients.

Stellar flares are also a concern for the *continuity* of habitability on the surface of orbiting planets. Due to their low stellar luminosities, habitable zones around cool stars lie very near the star (∼0.2 AU or less), making planets around these stars especially vulnerable to the effects of stellar activity. The cumulative effect of high energy irradiation by flares may impact the evolution and eventual habitability of planets by driving atmospheric photochemistry and escape processes (Lammer et al. 2007). As the most numerous of potential planetary hosts, it is essential to understand how frequently and powerfully these stars flare.

2.4 Direct Measurements of Magnetic Fields

Most of our current knowledge of how activity depends upon fundamental stellar parameters is derived from measurements of "proxies" for the magnetic field – e.g., chromospheric or coronal emission. Recently, however, several methods that probe surface magnetic fields more directly have become available – among them Zeeman Doppler Imaging of stellar surfaces (Donati et al. 2006), measurements of Zeeman splitting in molecular bands of FeH (Reiners & Basri 2007), and observations of synchrotron radio emission (e.g., Berger 2006). The advent of these direct measurements of magnetic field strength will help disentangle the dependence of stellar *magnetic fields* on rotation, mass, and age from the dependence of *activity* on those same parameters (e.g., Reiners, Basri & Browning 2009).

3. Understanding Magnetic Field Generation in Low-Mass Stars

In stars like the Sun, the interface between the convective envelope and the stable radiative core is thought to play a major role in generating global-scale magnetic fields through dynamo action (e.g., Parker 1993; Ossendrijver 2003). Modern theories of the solar dynamo hold that this interface is crucial for two reasons: firstly because of its strong shear, revealed by helioseismology (e.g., Gough & Toomre 1991), and secondly because the stable stratification there may allow fields to be greatly amplified before becoming susceptible to magnetic buoyancy instabilities (e.g., Parker 1993). Simulations including a simplified "tachocline" – a shear layer at the base of the convection zone – have yielded solar-like magnetic fields (Browning et al. 2006), though still without the orderly reversals of polarity that characterize the Sun. If, as these theoretical considerations suggest, the tachocline is essential in building the Sun's ordered magnetic field, then similar boundary layers are probably likewise important in the dynamo action of any star that has both a convective envelope and a radiative core.

But not all stars are configured like the Sun. At a spectral type of ∼M3 (0.35 $M_\odot$; e.g., Chabrier & Baraffe 1997), stars become fully convective and the tachocline presumably disappears. In such fully convective stars, a solar-like interface dynamo is precluded – and so a very basic theoretical prediction had been that these stars should show magnetic behavior that is qualitatively different from that seen in their more massive cousins (e.g., Durney, De Young, & Roxburgh 1993; Chabrier & Kuker 2006).

Recent observations, described in §2, have confounded even this basic prediction and presented major challenges to theory. The strong activity of low-mass stars, their surprisingly large-scale magnetic topologies, and the intricate links between rotation and magnetic activity, are all either wholly or partly unexplained. We focus below on two basic questions raised by these observations: **Q1: What is the role of rotation in generating magnetic fields?** and **Q2: How does the dynamo process depend on mass?** Both are, we believe, answerable in the coming decade, due to a rare confluence of new observational techniques and sophisticated computing tools.

We advocate a two-pronged approach that a) seeks to clarify the observational dependence of magnetic activity (and its proxies) on rotation rate and stellar mass; and b) seeks to understand the origin of these trends through numerical simulations and theoretical modeling. We have described in §2 a possible observational program that would yield advances in the *characterization* of low-mass star activity. Here, we comment briefly on the possibility of understanding these trends on theoretical grounds within the next decade.

3.1 Theoretical Developments and Prospects

Recent theoretical modeling of the dynamo process has begun to provide insights into how field generation may depend upon mass and rotation rate, but fundamental puzzles remain. The central challenge in modeling stellar dynamos is that the interiors of stars are intensely turbulent, with motions (and magnetic fields) spanning an enormous range of spatial and temporal lengthscales. The magnetohydrodynamic equations that govern the dynamo are not generally analytically solvable, so much attention has focused on numerical simulations of the dynamo process. Such simulations cannot hope to resolve all the physical scales present in real stars – which would plausibly require of order 10^{18} resolution elements – and so have generally fallen into two camps: one that chooses to model a localized domain at high resolution (e.g., Stein & Nordlund 1998; Cattaneo et al. 1991), and another that models the whole star but captures only larger scales of motion (e.g., Brun et al. 2004; Browning 2008). The former class of models have sometimes included sophisticated radiative transfer treatments and non-trivial equations of state; the latter have typically been more idealized, adopting ideal gas equations of state and simple diffusion approximations for radiative transfer. Global simulations are needed to understand large-scale field generation, but fall short when applied to surface phenomena or non-ideal interiors.

Despite the many simplifications made, global simulations of dynamo action in fully convective dwarfs have hinted at the deep role rotation may play in setting field strength and morphology (Dobler, Stix & Brandenburg 2006; Browning 2008). *But to fully understand how magnetic activity varies with rotation rate and mass, we believe two major improvements to current large-scale simulations will be required: a) more realistic physics, particularly with respect to the equation of state, and b) higher resolution.* The former improvement will allow modeling that extends to the very low-mass regime, where degeneracy effects may play an important role in the interior, and where increasingly cool and neutral atmospheres likely complicate field emergence (e.g. Mohanty et al. 2002). The latter will allow global-scale models to extend closer to the stellar surface, including both broad motions that overturn slowly and small-scale turbulence that does not feel the effects of rotation (but may play an important role in angular momentum redistribution and dynamo action).

These advances will be enabled by an extraordinary expansion of computing power, with several major new resources expected to come on line in the next 2-3 years. The NSF has already begun soliciting proposals for a "petascale" machine (10^{15} floating point operations per second), to come on line in 2011 or 2012, which will enable simulations that are larger in scale (or higher resolution), more realistic in their treatment of the physics, and runnable for the long timescales needed to address activity in the time domain – e.g. magnetic cycles or rare events like flares. Significant new challenges will have to be met in order to use this next generation of machines effectively: codes will have to scale well up to hundreds of thousands of processors, and new methods will need to be developed to query and visualize many-terabyte datasets. But these efforts are necessary if we are to understand the dynamo process in low-mass dwarfs specifically, or stars more generally.

4. Summary of Recommendations

Understanding magnetic activity at the bottom of the Main Sequence helps to place our Solar System in context, both by elucidating the extent to which our Sun is representative of other stars, and by constraining whether the majority of stars in our Galaxy can be expected to host habitable planets.

To answer some of the outstanding questions we have raised here, we advocate a two-pronged approach that a) seeks to clarify the observational dependence of magnetic activity (and its proxies) on rotation rate and stellar mass; and b) seeks to understand the origin of these trends through numerical simulations and theoretical modeling. With this in mind, we have identified 3 particular courses of action that address outstanding questions:

- *Large–scale, deep spectroscopic surveys* – such surveys would determine the presence, level and duration of activity for the coolest stars and brown dwarfs.
- *Time domain studies of the stellar flare rate* – these observations would place strong constraints on heating and energy storage by magnetic fields.
- *Non-optical surveys, particularly in the X-ray and UV* – observations that would help assess the total chromospheric/coronal radiative losses for active stars, and would inform models of planetary atmospheric evolution for attendant planets.

These new data will, in turn, inform developing theoretical models of magnetic field generation, which will be poised to become more realistic and detailed in the years to come.

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