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Magnetic Activity in Low Mass Stars and Brown Dwarfs

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Abstract. We first review the state of our knowledge of magnetic activity in low mass stars, concentrating particularly on chromospheric diagnostics, spots and flares. We then discuss observations of very late M dwarfs, and L dwarfs, and describe the similarities and differences in magnetic activity as compared to the earlier type stars. The observed changes in activity as a function of mass lead to theoretical consequences for dynamo models in these objects.

1. Introduction and Review of Results for Solar Type Dwarfs

Magnetic activity is a generic term traditionally used to describe a wide range of observable phenomena produced in the outer atmospheres of cool stars. We now know that at least some aspects of magnetic activity are present in brown dwarfs, and eventually we may hope to find a connection between the behavior of low mass brown dwarfs and the magnetic phenomena observed on giant planets such as Jupiter. The decades of data collected on solar type and M dwarf stars provide an excellent starting point for the analysis of the lowest mass stars and brown dwarfs.

Solar type (spectral types G-K) dwarfs, and in particular the Sun, were the first objects to undergo intensive scrutiny. The field began with the observation of sunspots by Galileo and proceeded with the identification of sunspots as regions of intense magnetic field by Hale and with the qualitative explanation of cyclic sunspot behavior by Babcock. It is now fairly well accepted that the surface magnetic field on the Sun, and other G-K dwarfs, is powered by an internal dynamo which depends on rotation, and particularly differential rotation. The field is generated and stored at the boundary between the convection zone and the radiative zone (hence the common name "shell dynamo"). Magnetic flux tubes rise to the surface due to buoyancy and appear as sunspots (which are the footpoints of the tubes) and coronal loops (seen as closed X-ray emitting structures in satellite pictures). The field strength of a typical flux tube in the solar photosphere is B $\sim$ 1000G, and flux tubes cover $\sim$ 1% of the solar surface area. The atmosphere within the loops is heated by some non-radiative process which is not yet well characterized, but may take the form of Alfven wave dissipation. This magnetically heated atmosphere is comprised of the chromosphere (T $\sim 10^4$K), transition region (T $\sim 10^5$K) and corona (T $\sim 10^6$K) with each region producing emission line radiation from optically thin, collisionally excited species; ionized calcium and magnesium and hydrogen recombination lines in the chromosphere, moderately ionized light metals such as C IV in the transition region, and highly ionized heavy metals such as Fe XIX in the corona. A typical temperature structure for the magnetically-heated solar outer atmosphere is shown in Figure 1a.

Sunspots are easily observed with high spatial resolution on the Sun, and have also been observed on other G-K dwarfs as periodic photometric variations with the rotation period of the star. The Sun exhibits an 11-year cycle in the number and location of sunspots; cyclic behavior in other solar type stars has been observed in the Ca II emission lines near 4000Å, which emit a large fraction of the radiation from the solar chromosphere (Baliunas et al 1995). A notable result is that the most active (i.e. showing the strongest emission lines) G-K dwarfs are less likely to show cyclic behavior than relatively inactive stars like the Sun. Flares are yet another manifestation of magnetic activity, occurring in association with sunspot groups or "active regions" and producing, for a brief period, huge enhancements in the solar luminosity in some wavebands (X-rays, optical and ultraviolet emission lines, microwaves).

The fraction of G-K dwarfs that are observed to be active is directly related to the dependence of the magnetic field generation on rotation rate. As solar type dwarfs lose angular momentum and spin-down during their evolution on the main sequence, they become less active, following an age-activity relation of the form (Ca II emission flux) $\propto$ (time)$^{-\alpha}$, with values of α near 0.5 (as first proposed by Skumanich 1972). Calibration of the relation is accomplished using data from open clusters, and shows that active G-K stars are quite young, age $\lesssim$ 100 Myr, while stars of the Sun's age are relatively inactive, leading to a small active fraction in the overall disk population. The amount of the bolometric luminosity that is emitted by the outer atmosphere, and during flares, is also quite low for all but the most active of these stars.

2. Results for Early - Mid M dwarfs

In contrast to solar type stars, the magnetic field in early-mid M dwarfs often dominates the stellar surface, with B $\sim$ several thousand Gauss and filling factors of 50% or more (Johns-Krull & Valenti 1996). The field is not only stronger and more pervasive, but the higher gravity in the M dwarf atmosphere (resulting in higher pressure, hence higher density at a given temperature) means that the non-radiative heating rate, often taken to be constant per unit mass, is enhanced. In response, the atmosphere radiates more efficiently and the emission lines are much stronger, particularly the hydrogen Balmer lines which become the dominant radiation mechanism in the chromosphere. The change in chro-

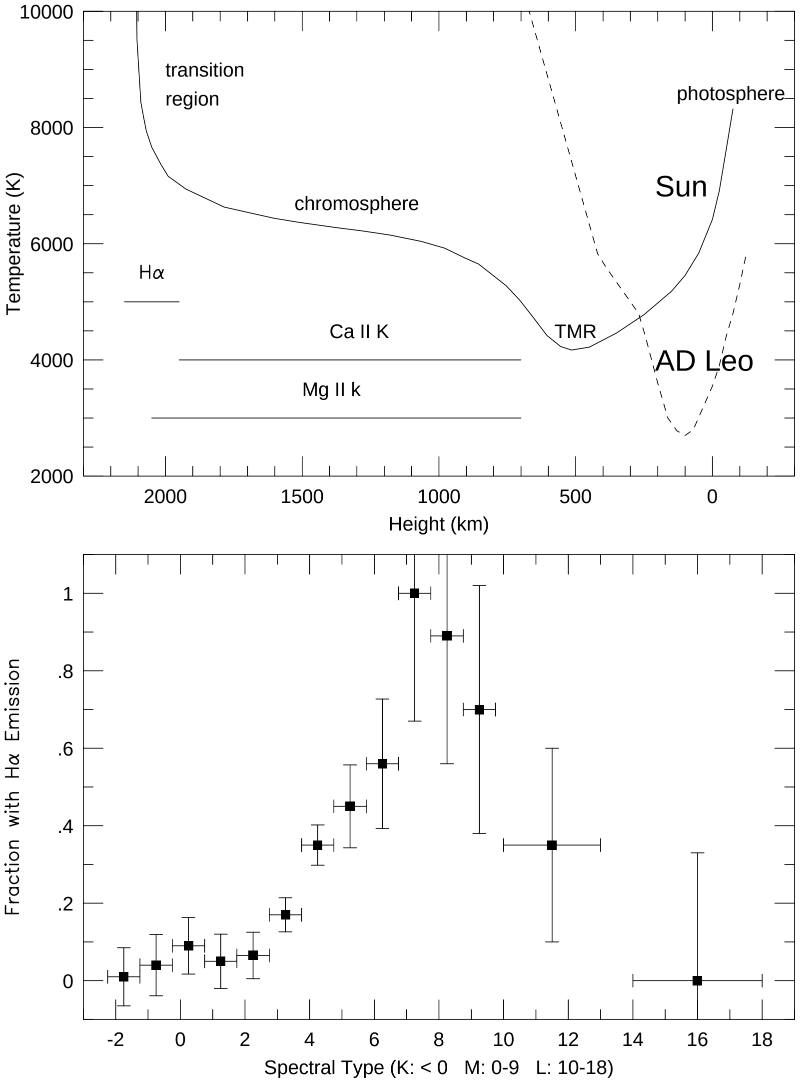

Figure 1. a) The VAL3C (Vernazza et al 1981 - solid line) solar atmospheric model is compared to a model for the active dM3e star AD Leo (Mauas & Falchi 1994 - dashed line). The Ca II, Mg II and H emitting regions are shown for the solar case, and the various regions of the atmosphere - photosphere, temperature minimum region (TMR), chromosphere, and transition region - are labeled. b) The fraction of M dwarfs that are magnetically active reaches a maximum at spectral type M7 and declines at both earlier and later spectral types.

mospheric structure compared to the Sun can be seen in Figure 1a for the active dM3e star AD Leo.

Although rotational modulation has been observed on a few M dwarfs, spots are not nearly as common as in solar type dwarfs, provoking speculation that the surface is completely covered with spots (often known as "saturation", although uniform but not complete coverage of small spots would provide the same effect). There is no good evidence for organized spot cycles in stars cooler than spectral type M0 (Bondar 1995). In contrast, flares are very common and have been observed even on M dwarfs with no quiescent Hα emission. A vast range of flare energies has been measured, and the distribution (number of flares of a given energy) appears to be similar among the early-mid M dwarfs (Lacy et al 1976). M dwarf flares emitting several orders of magnitude more energy than the largest solar flares have been observed.

The M dwarfs have long been known to show an increasing activity fraction toward later spectral type (lower mass) (Joy & Abt 1974). Only a few percent of early M dwarfs (M0-M3) are active, but by M7 essentially all known M dwarfs show activity as evidenced by Hα emission (Hawley et al 1996, Gizis et al 1999). Figure 1b illustrates this rise in the activity fraction (and subsequent decline at even later spectral types; we will discuss this in more detail later). While it is true that Hα becomes easier to observe as the continuum flux near 6560Å decreases in later-type objects, the rising activity fraction result is not due to an observational selection effect. Figure 2a shows that, although there is a large scatter in the activity strength, (defined to be the luminosity emitted in the Hα line compared to the bolometric luminosity of the star, log $L_{H\alpha}/L_{bol}$) it is much higher for most active M dwarfs than for their higher mass G-K counterparts, with a typical value of 10^{-4} L_{bol}. The average activity strength remains high even in the later type stars. Observationally, this means that later type stars have emission lines with larger equivalent width, to compensate for the decreased continuum flux. Note that the scatter in the activity strength increases significantly in going from spectral type M0 to M7, with values larger and smaller than the average becoming common.

The increase in the activity fraction is a manifestation of the age-activity relation for M dwarfs, which differs significantly from the G-K dwarf relation. Instead of showing decaying emission with age, the early-mid M dwarfs show steady levels of emission *which lasts longer at later spectral type.* This age-activity relation has been calibrated using open cluster data and results in ages of M0 stars $\lesssim$ 1 Gyr as compared to $\lesssim$ 5 Gyr for M4 stars (Hawley et al 1999). Thus, most M4 (and later) stars in the general disk population are still active, as observed. The explanation of angular momentum evolution, hence declining rotation rate and reduced dynamo activity, that works so well for the G-K dwarfs does not prove adequate for the M dwarfs. Figure 2b shows that M dwarfs may have the same activity level over a large range of rotation rate, down to the observational limit of $\sim$ 2 km/sec as shown in the figure. In fact, the well-observed star Proxima Centauri actually has significant activity despite its rotation rate of $\lesssim$ 0.2 km/sec (Benedict et al 1999). Most velocities in the figure for early-mid M dwarfs come from Delfosse et al (1998); measurements for the later type dwarfs come from a variety of sources, described in detail in Reid & Hawley (2000).

Because the M dwarfs are predicted to be fully convective by spectral type M3-4, the shell dynamo model used for the sun cannot be directly applicable. Durney et al (1993) have proposed a turbulent dynamo model (also sometimes called a distributed dynamo) that relies on field generation through random convective motions rather than on organized, rotationally-driven flows. Though still qualitative, this model does satisfy the observational constraint of a weak (or no) dependence on rotation.

3. Results for Late M and L dwarfs

The past year has seen a huge surge in the data available for the latest M dwarfs (spectral types M8 and later) and the identification of the new "L" spectral type to describe even later type dwarfs (see paper by Kirkpatrick et al in these proceedings). Of course the data are still less complete than for the solar type and earlier M dwarfs which have been observed for decades. For example, no direct measurements of magnetic fields have yet been made and so we have no information on typical field strengths and filling factors. Spots have been observed on a few objects (Martin & Zapatero-Osorio 1997; Terndrup et al 1999), but none have been monitored long enough to comment on spot cycles. A few flare events have been detected while obtaining survey information; flares have been seen both in Hα and in X-rays (Liebert et al 1999; Fleming et al 1999). Previous data on the late M dwarfs VB 10 and LHS 2397a had shown flares in Hα and in transition region lines (Herbig 1956; Bessell 1991; Linsky et al 1995). The few flares observed thus far have been exceedingly energetic, near the maximum in L_{flare}/L_{bol} seen in the early-mid M dwarfs, indicating that the distribution of flare energies may differ significantly from the earlier type stars.

The late M and L dwarfs do show evidence of quiescent chromospheric radiation, with Hα detections in many stars including some of the newly identified L dwarfs. It is not known whether Hα is still the dominant emission mechanism or whether structural changes in the atmosphere have altered the heating and cooling, as occurred between the solar-type and early M dwarfs. However, there are as yet no known late M or L dwarfs which have detectable X-rays or non-thermal radio emission in their quiescent (non-flaring) state (Krishnamurthi et al 1999; Fleming et al 1999). There are a few *brown* dwarfs with quiescent X-ray emission, but these are all very young objects with earlier spectral types (M5-M6) (Neuhauser et al 1999). There is a very strong age dependence of the spectral type in a brown dwarf (see discussion by Burrows in these proceedings). Thus it will be difficult, but important, to disentangle the effect of the temperature of the atmosphere (spectral type) and the effect of the internal structure (which depends on the mass, determining whether the object is a brown dwarf or a star) on the observed magnetic activity.

The fraction of late M and L dwarfs which show Hα in emission, hence magnetic activity, decreases with later spectral type as shown in Figure 1b. The M8-L0 objects are taken from Gizis et al (1999); the L dwarfs come from Kirkpatrick et al (1999). No objects later than L3 have yet been found to have Hα emission. Again the sample represents a mixture of brown dwarfs and very low mass stars at different ages, and we stress that Hα may no longer be a good measure of activity in some or all of these objects. Figure 2a shows that

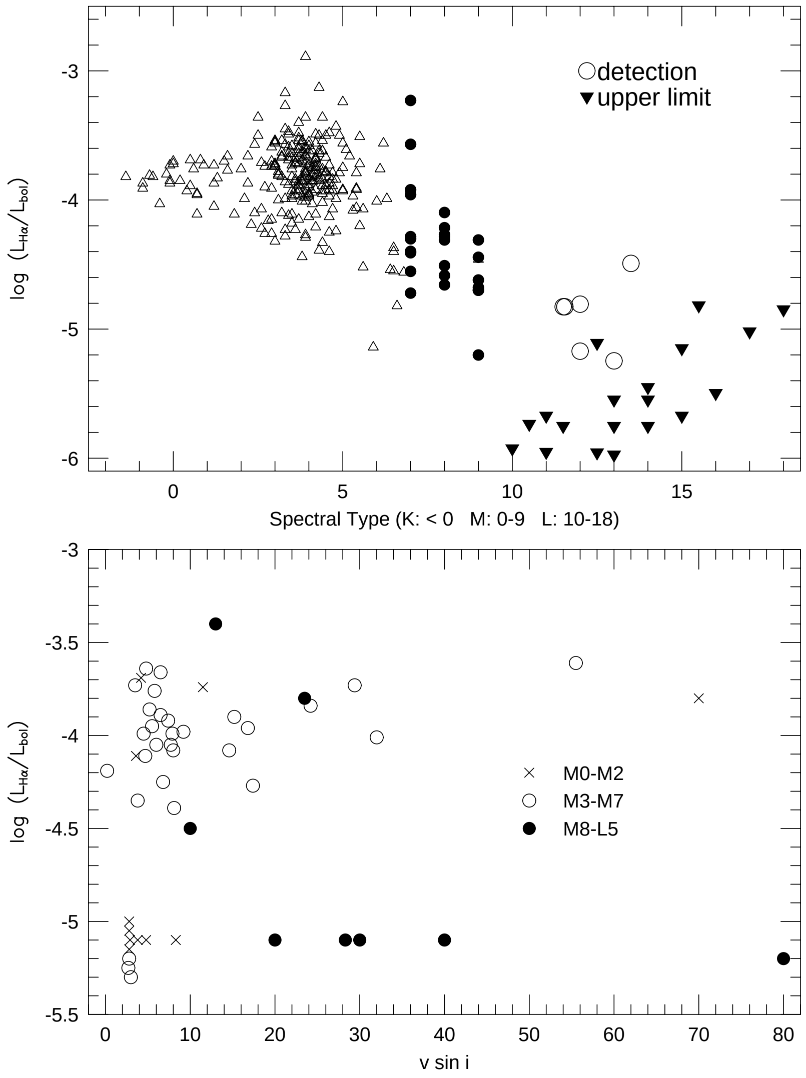

Figure 2. a) The activity strength, log ($L_{H\alpha}/L_{bol}$), vs. spectral type showing that the average activity strength remains high through spectral type M7 and declines thereafter. b) log ($L_{H\alpha}/L_{bol}$) vs v sin i showing that M dwarfs may be equally active at a wide range of rotation rate. Inactive stars are shown at log ($L_{H\alpha}/L_{bol}$) $\sim$ -5.1; several are at the observational limit near 2 km/sec and have been arbitrarily offset so they can be seen. Note that inactive objects at late spectral types can have quite large rotation velocities.

the activity strength begins to decline in these late type objects after spectral type M7. Gizis et al (1999) point out that the activity strength in the M8-L0 dwarfs is correlated with tangential velocity such that objects with strong activity have higher velocities, indicating that they are kinematically old (and thus are probably stars).

Another interesting observation is shown in Figure 2b; many of the latest type dwarfs are rotating quite rapidly, but the rotation is, if anything, anti-correlated with the activity strength. This result was first noted for the object BRI0021-0214 by Basri & Marcy (1995), and has since been confirmed by several other studies (e.g. Tinney & Reid 1998). Another noteworthy object is PC0025+0447, which is the closed circle at v sin i = 13 km/sec and activity strength near -3.4. This M9.5e dwarf has an enormous Hα equivalent width (several hundred Å) and no Ca II emission. A detection of lithium has recently been reported, indicating that it is probably a young brown dwarf (Martin et al 1999). It also has a high, but not excessive activity strength compared to the earlier type dwarfs (it is not present in Figure 2a which came from a different survey), and rather slow rotation for its spectral type. These data indicate that the relationship between rotation and activity is much different for the M and L dwarfs compared to the solar type stars described above.

4. Discussion

Table 1 summarizes the magnetic properties of solar-type stars, early-mid M dwarfs, and late M-L dwarfs. Notable trends include:

1. Spots become less prevalent in later type objects, perhaps indicating that the field is less organized (many small spots located over the whole surface rather than a few large ones at specific locations). Cycles are not seen at later type which also indicates a more chaotic, and in the case of the solar type stars without cycles, a stronger field.

2. Chromospheric radiation switches from Ca II/Mg II produced at relatively low temperature in solar type dwarfs, to Hα produced at somewhat higher temperature in early-mid M dwarfs, and perhaps to even higher temperature diagnostics in the latest type objects, if the trend continues. Flares become increasingly energetic at later types (compared to the bolometric luminosity of the object), further supporting the view of more chaotic fields and higher energy atmospheres.

3. The activity fraction increases through the early-mid M dwarfs, peaks at M7 near 100% and declines at later types. The average activity strength remains high but the scatter increases through the M0-M7 range. This is an age effect - the activity lasts longer in the later type stars. At the latest types, there is some evidence (X-rays) that only very young brown dwarfs are active, while stars remain active as the tail of the M dwarf distribution. Samples of late M and L dwarfs include both brown dwarf and stellar populations making global conclusions based on spectral type alone suspect.

4. Magnetic activity is well correlated with rotation in the solar type stars, but this correlation breaks down in the M dwarfs. In the latest M and L dwarfs, rotation seems to be irrelevant, or possibly even anti-correlated with activity.

Table 1. Summary of Magnetic Properties in Low Mass Dwarfs

Feature	Solar-type	early-mid M	late M - L
Magnetic fields	yes	yes	?
B, filling factor	1000G, 1%	3000G, 50%	?
spots	yes	yes (some, low amp)	yes (some, low amp)
cycles	yes	no	?
flares	yes	yes	yes
chromospheric radiation	Ca II/Mg II	Hα	Hα?
fraction that are active	small	increasing –> all	decreasing –> none
activity strength	weak	strong, large scatter	weakening –> none
rotation	correlated	weak/none (threshold?)	none/anti-correlation? fast rotation inhibits?
radio, Xrays	yes	yes	only in very young
age behavior	decays with time	lasts longer at lower masses	only occurs in young BD or old stars?
dynamo	shell	turbulent	turbulent –> none (primordial?)

Figure 3 is a schematic diagram which attempts to draw together the observed magnetic properties into a coherent physical scenario for a low mass dwarf population of a given age (it is not an evolutionary diagram!). It incorporates the decline of the shell dynamo and rise of a turbulent dynamo in producing the magnetic field as the atmosphere loses its radiative core and becomes fully convective between the solar type and mid M dwarfs. A possible primordial component exists at all types, though it may decay with age. The shell dynamo depended on rotation so only a few of the stars at this age have ample rotation to produce significant activity. The turbulent dynamo, in contrast, depends on the convection and all stars have activity, though with varying degree, in this picture. The field produced by the turbulent dynamo is more chaotic, resulting in fewer large organized spots, the disappearance of spot cycles, more (and larger) flares. It is still unclear why the activity lasts longer at later spectral types, though it could be related to the strength of the convection. At late spectral types, several effects may become important in quenching the magnetic activty. The onset of dust formation in the atmosphere may produce a radiative zone that could inhibit the emergence of the field; the weakening of the convection as the atmosphere becomes cooler and/or the growth of the degenerate core could inhibit the production of the field. The role of the primordial field could be important, especially in brown dwarfs at very young ages.

We stress that the diagram is not meant to be quantitative and that it may vary considerably at different ages of the population. However, it does provide a

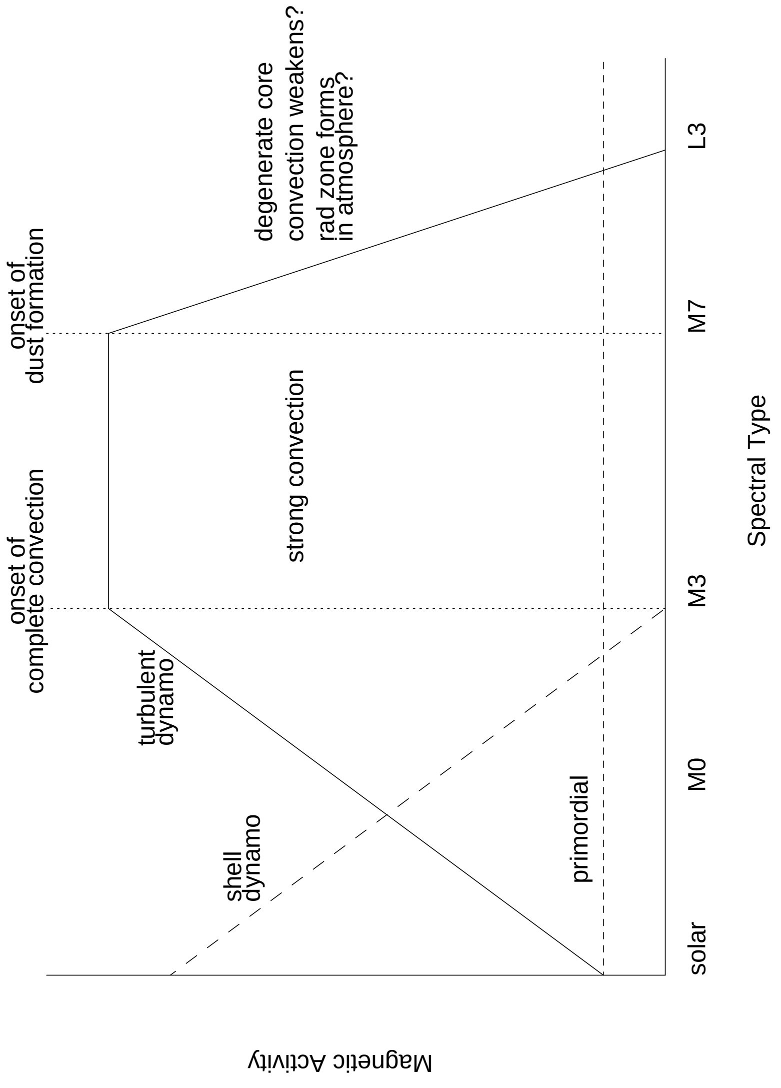

Figure 3. Schematic diagram of magnetic activity as a function of spectral type, illustrating some of the important physical attributes that may contribute to changes in activity.

starting point for discussion of the many facets of magnetic activity in low mass dwarfs that are still poorly understood.

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