Ultra-Cool and Extra-Vigorous: Rotation and Activity in M and L dwarfs

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The study of rotation and activity in low-mass stars or brown dwarfs of spectral classes M and L has seen enormous progress during the last years. I summarize the results from different works that measured activity, rotation, and sometimes magnetic fields. The generation of magnetic activity seems to be unchanged at the threshold to completely convective stars, i.e. no change in the efficiency of the magnetic dynamos is observed. On the other hand, a sudden change in the strength of rotational braking appears at the threshold mass to full convection, and strong evidence exists for rotational braking weakening with lower mass. A probable explanation is that the field topology changes from dipolar to small scale structure as the objects become fully convective.

1 Introduction

Rotation and activity are intimately connected in sun-like stars. Rotation is believed to generate a magnetic field through a dynamo mechanism that scales with rotation. The stellar wind couples to the rotating magnetic field lines carrying away angular momentum so that the star is being braked. Hence stars of spectral type F–K rotate more rapidly and are more active when they are young, but they decelerate and become less active as they age; this is the so-called rotation-activity connection (Noyes et al., 1984; Pizzolato et al., 2003).

The scaling of activity with rotation depends on the type of dynamo inside the star. The fact that the rotation-activity connection is similar in virtually all stars that harbor convective envelopes and at all ages (Pizzolato et al., 2003; Reiners, 2007) indicate that the dynamo mechanism is comparable in all these stars. Around spectral type M3.5, the internal structure of the stars changes; stars later than around M3.5 are believed to be fully convective. They cannot harbor an interface dynamo working at the tachocline, which is believed to be the most important dynamo mechanism in the hotter sun-like stars. If the interface dynamo was the only important mechanism driving a magnetic dynamo, one could expect a sharp break in magnetic field generation around spectral type M3.5. Such a break would imply a sudden change in observable stellar activity and in the braking of stellar rotation.

A break in stellar activity is not observed in X-rays or Hα in the surveys that crossed the M3.5 border (e.g., Delfosse et al., 1998; Mohanty & Basri, 2003; West et al., 2004). Activity rather stays at comparable levels if normalized to bolometric luminosity, and quite surprisingly the fraction of active stars even raises up to ~ 80% in late M-type objects before it goes down again. This clearly shows that the interface dynamo is not the only dynamo operating in stellar interiors and that fully convective stars can have quite efficient dynamos as well.

On the other hand, Delfosse et al., 1998, presented a plot that shows a different behavior in rotational braking in stars later than spectral type M3.5. In their Fig. 3, they show that all M dwarfs earlier than M3.5 are slow rotators (v sin i ≤ 3 km s⁻¹) regardless of what disk population they belong to (young or old). M stars later than M3.5, however, show substantial rotation velocities of up to v sin i = 50 km s⁻¹ in the young disk population, and in the old disk population some late M dwarfs still have velocities around v sin i = 10 km s⁻¹. This can be interpreted as an indication for a sudden change in the timescales of rotational braking at the mass where stars become fully convective. Delfosse et al. conclude that spin-down timescales are on the order of a few Gyrs at spectral type M3–M4, and of the order of 10 Gyr at spectral type M6.

The investigation of rotation and activity in ultra-cool stars (M7 and later) was put on firm ground by Mohanty & Basri, 2003. From high-resolution spectra they determined projected rotation velocities, and from Hα emission they derived the level of activity. Reiners & Basri, 2007, added more M stars to this sample. In addition, they measured magnetic fields in low-mass M dwarfs and showed that in M dwarfs the level of activity is still coupled to magnetic flux – high magnetic flux levels lead to strong Hα emission and stars without Hα emission show no magnetic fields.
Activity in low mass stars is usually measured in terms of \( \log L_{\mathrm{H}\alpha}/L_{\mathrm{bol}} \). It can be calculated from the equivalent width of the H\( \alpha \) line using flux calibration from spectral models (e.g., Mohanty & Basri, 2003). Fig. 1 shows the values of \( \log L_{\mathrm{H}\alpha}/L_{\mathrm{bol}} \) for the results of Delfosse et al., 1998; Mohanty & Basri, 2003; Reiners & Basri, 2006; and the new L dwarf data. The stars for which magnetic flux measurements are available in Reiners & Basri, 2006, are plotted with filled symbols distinguishing between three groups of strong, intermediate and little magnetic flux (see caption of Fig. 1). All other detections of H\( \alpha \) emission are shown by open circles, non-detections by downward arrows. I also plot the results from Hawley et al., 1996, in small grey circles. They come from less sensitive spectroscopy so their detection limit is higher than limits from high resolution spectroscopy.

The measurements from Hawley et al., 1996, are part of a large survey among nearby M stars that extends to early M dwarfs. Normalized activity scatters around \( \log L_{\mathrm{H}\alpha}/L_{\mathrm{bol}} = -4 \) and shows no break at the threshold to complete convection (~M3.5). Results from the other surveys show that this activity level is maintained up to at least M7 before the general level of activity gradually decreases. This decrease is believed to be due to the growing neutrality of the atmosphere (Mohanty et al., 2002) and does not necessarily imply a less efficient dynamo mechanism.

Activity is observed in objects as cool as spectral type L5 \(( T_{\text{eff}} \approx 1700 \, \text{K}) \). Especially among the L dwarfs, a number of objects was observed more than once, and the data points that belong to the same objects are connected with solid lines. Some L dwarfs show large variability in H\( \alpha \), i.e. they frequently show flaring activity. In the few objects that are as late as L7–L8 \(( T_{\text{eff}} \approx 1500 \, \text{K}) \), no H\( \alpha \) activity was detected. Whether this means that objects as cool as this are inactive, or that their activity level is just below the detection limit is an open question (see also Burgasser et al., 2002).

Measuring rotation velocities requires spectra of higher quality than the detection of the H\( \alpha \) emission line. A comparison to artificially broadened synthetic spectra becomes increasingly difficult with later spectral type, because a) the synthetic spectra systematically provide a worse match to the spectral details as more and more molecular features shape the spectrum (and dust begins to form in the atmosphere), and b) the typically broad molecular features are less affected by rotation broadening than sharp atomic absorption lines so that the accuracy of \( v \sin i \) measurements in M and L dwarfs is usually lower than in sun-like stars.

In Fig. 2, I show as filled circles the results of \( v \sin i \) measurements in M- and L-dwarfs from Delfosse et al. (1998); Mohanty & Basri (2003); Reiners & Basri (2007); and from new L-dwarf measurements. In contrast to the

**Fig. 1** Normalized H\( \alpha \) activity \( \log L_{\mathrm{H}\alpha}/L_{\mathrm{bol}} \) vs. spectral type. Filled symbols mark stars with measured magnetic flux; upward triangles are stars with high magnetic flux \(( B_{\text{f}} > 3 \, \text{kG}) \), squares denote stars with intermediate flux level \(( 3 > B_{\text{f}} > 1 \, \text{kG}) \), and downward triangles mean no or little magnetic flux \( B_{\text{f}} < 1 \, \text{kG} \). Open circles are from high resolution spectra from different sources (see text). Small grey circles are taken from Hawley et al., 1996.

**Fig. 2** Projected rotational velocities \( v \sin i \) as a function of spectral type. Results from field star investigations (see text) are plotted as circles. Stars mark the three components of LHS 1070, which are probably of same age. The filled squares show two sub-dwarfs that are probably as old as the galaxy itself. The dashed line shows the approximate lower envelope of rotation velocities.
early M dwarfs of spectral type earlier than M3 (see Delfosse et al., 1998), many objects exhibit significant rotation rates. Mohanty & Basri (2003) already showed that L dwarfs are probably rapidly rotating in general, and that there might be a lack of slowly rotating L dwarfs. With the new observations, it has now become obvious that slow rotators are rare among the visible L dwarfs. The dashed line in Fig. 2 marks the lower envelope of rotational velocities as a function of spectral type that seems to limit the lower end of rotation rates in ultra-cold dwarfs. The few exceptions may well be due to projection effects, i.e. the two “slow” rotators at spectral types L1 and L7.5 may be observed pole-on.

Many of the ultra-cold dwarfs are probably brown dwarfs that do not establish a fixed temperature, they rather keep cooling down the spectral sequence. If they are being rotationally braked, they do not follow vertical tracks in \( v \sin i \) at constant spectral type in Fig. 2, but they rather evolve for example from rapidly rotating mid-M dwarfs to slowly rotating late L dwarf as they follow the evolutionary tracks.

A possible scenario could be that the rotationally braked slow rotators are old objects that are much fainter than their rapidly rotating predecessors. The slowly rotating L dwarfs could simply be too faint for the samples, and the dashed lower envelope could be due to an observational bias. A few arguments though contradict the picture of an observational bias. First, in this scenario rotational braking of ultra-cool objects must follow quite accurately the cooling of the objects (independent of their mass), and the distribution of ultra-cool objects must be very homogeneous. Second, there are two observed systems indicating that the spread of rotational velocity with spectral type is indeed mass (or temperature) dependent, not time dependent: 1) Reiners et al. (2007) have recently taken spectra of the triple system LHS 1070. The system consists of three M dwarfs, one mid-M dwarf of spectral type M5.5 and two late-M dwarfs. Although the three objects are probably coeval, the two late M objects are rotating twice as fast as the more massive mid-M object. This indicates that at the same age the two cooler objects went through the same rotational history while the third, more massive component suffered stronger rotational braking. 2) Two ultra-cold sub-dwarfs were investigated by Reiners & Basri (2006). Late-type sub-dwarfs are probably metal poor relics of the early galaxy and have had billions of years to slow down their rotation rate. The two objects are indicated with filled squares in Fig. 2. While the sdM7 dwarf does not exhibit any signs of rotation, the sdL7 object still rotates at very high velocity, \( v \sin i \approx 65 \, \text{km} \, \text{s}^{-1} \). This is a very strong argument that we can indeed see the oldest L dwarfs even at late spectral class, but that they are still rotating at very high pace.

5 Summary and Conclusions

High resolution spectroscopy in M and L dwarfs becomes a technique that allows to investigate the physics and the evolution of low mass objects in great detail. No change in H\(\alpha\) activity is observed at the threshold to complete convection. Activity can be followed to objects as late as mid-M and it might continue to even lower masses but below the current observational threshold. The decline in normalized activity among the ultra-cool dwarfs could be explained by the enhanced electrical resistivity at the low temperatures. Currently, no indications for a mass or temperature dependence of stellar or substellar dynamos can be concluded from the activity measurements.

A sudden change in the behavior of rotational braking at spectral class M3.5 was already found by Delfosse et al., 1998. In the young disk, stars earlier than M3.5 rotate slowly while later stars still show significant rotation. The lack of slowly rotating ultra-cold dwarfs and the rise of the minimum rotation rate with spectral class could be explained by rotational braking that is weaker with lower mass or lower temperature. The reason for a weaker braking at later spectral type could be a different magnetic topology. The geometry of the magnetic field is essential for the strength of magnetic braking as described in Krishnamurthi et al. (1997) and Sills et al. (2000). These authors find that the description of magnetic braking (\( \omega_{\text{crit}} \)) needs to be different in mid-M stars and in earlier objects, which they connect to different convective turnover times.

Although the details of magnetic braking in ultra-cold dwarfs are not quite understood, a substantial amount of evidence exists that rotational braking is weaker with lower mass or lower temperature. The limiting factor of rotational braking may be the topology of the magnetic fields which in fully convective stars might be generated on smaller scales so that the topology is different from a dipolar configuration leading to the weaker rotational braking.

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