Part 8

Activity and Weather

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Magnetic Activity and Rotation in Brown Dwarfs and Low Mass Stars

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Abstract. One of the triumphs of the last 2 decades has been the establishment of the relation between stellar rotation and magnetic activity in solar-type stars. Rapid rotation produces strong activity, which in turn provides magnetic braking to reduce rotation. A solar-type dynamo cannot operate in fully convective stars, so it is of interest to study mid and late M stars. Hints that a dramatic change occurs in very low-mass stars and substellar objects appeared in 1995. The past 7 years have seen substantial progress on this question, with the conclusion that the rotation-activity connection indeed breaks down. As one goes to the bottom of the main sequence and below, the amount of magnetic activity takes a sudden fall, with a concomitant increase in the spindown times of the objects. We summarize these results, and some theoretical work which helps explain them. We also present some remaining mysteries, such as why very young objects seem excessively active, and flaring in objects with no other signs of magnetic activity.

1. Introduction

A connection between the rotation of a convective star and the amount of magnetic activity has been noted since the 1960s (e.g.,. Kraft 1967). Magnetic activity can be characterized by CaII emission, Hα emission, UV emission lines (once spaceborne spectra became available in the late 1970s) or coronal (X-ray) emission (from the Einstein satellite onward). The activity can be characterized by the surface flux in the given diagnostic, or by a luminosity ratio between the diagnostic and the stellar bolometric luminosity. The latter is easier to measure (not requiring knowledge of the stellar parameters beyond a bolometric correction), but assumes that there is some connection between the two luminosities. Rotation is usually measured through Doppler broadening of spectral lines (which only gives the projected rotation velocity), or by detecting a periodic rotational modulation of magnetic features (utilizing a broadband luminosity).

Noyes et al. (1984) showed that for solar-type stars, the activity characterized by *luminosity ratios* is a strong function of the Rossby number (the ratio of the rotation period to a convective eddy timescale, properly chosen). This is expected in certain dynamo theories. The solar dynamo is thought to be of the $\alpha\omega$ variety, operating in the shear layer between the convective and radiative zones. This naturally leads to a connection between rotation and activity. A good review of this overall subject can be found in Charbonneau et al. (1997).

In fully convective pre-main sequence stars or stars with masses less than $0.3M_{\odot}$, there is no shear boundary. Dynamos in these stars must either be turbulent (which would only weakly depend on rotation), or of the α^2 variety (which would have a strong rotational dependence). There is no reason why only one mode must be active. The Sun at minimum activity may be displaying primarily a turbulent or α^2 mode, while the cyclic increase and decrease (and extra activity therein) could be due to the $\alpha\omega$ dynamo. The relative contributions of these two probably shifts as stars have deeper convection zones, with the importance of the $\alpha\omega$ dynamo diminishing in cooler stars. This would explain why nothing special seems to happen at the fully convective boundary for main sequence stars. An expanded version of this discussion can be found in Mohanty & Basri (2002).

A further phenomenon is found in rotation-activity studies, called "saturation". This is a tendency for the amount of activity to achieve a maximum at a certain rotation rate, beyond which increasing the rotation no longer increases the activity. The reasons for this are not understood; it may be a characteristic of the dynamo production of fields, it may reflect full coverage of the surface or atmospheric volume by fields with no room to add more, or it could be an effect of the rapid rotation. The activity levels on the Sun are well below saturation even at its most active phase. L_X/L_{bol} for the Sun is in the range of 10^{-6}, while this quantity saturates at about 10^{-3} for M stars. The rotation velocity needed to cause saturation is about 15 km s^{-1} for G stars, 10 km s^{-1} for K stars, dropping to 5 km s^{-1} for early M stars. There may also be a phenomenon called "super-saturation", in which extremely rapidly rotating stars are less active than the saturation limit (e.g.,. James et al. 2002). For early M stars, the rotation-activity relation below saturation is not really known, because the stars are generally rotating too slowly to obtain a specific knowledge of it.

2. Rotation and Activity in Very Cool Stars

Very little was known about stars later than M5 in the early 1990s. The modern era of large telescopes had not yet gotten underway, and the largest telescopes were the Palomar 5-m and a few 4-m telescopes. Little of their time had been devoted to studying late M stars. The spaceborne observatories then had too little sensitivity to the much smaller fluxes of high energy radiation from these objects (even if they have large surface fluxes, they have small surfaces). The study of the rotation-activity relation in such objects began on the first general observing run at the newly commissioned Keck I telescope (in Nov. 1993) using the HIRES echelle. The results of this run produced "A Surprise at the Bottom of the Main Sequence : Rapid Rotation and no Hα Emission" (Basri & Marcy 1995). One of the coolest known objects at the time, BRI 0021-0214 (M9.5), had a bafflingly smooth spectrum. This was found to result from rotation at 20 times the usual rate for M field dwarfs (less than a 3-hour rotation period!). Normally such rapid rotation would be accompanied by strong stellar activity, but there was no observed Hα emission (generally we will use this as a proxy for magnetic activity unless otherwise stated). The authors noted that as one goes to late M stars, the equivalent width of Hα becomes increasingly sensitive to chromospheric heating (a given equivalent width corresponds to decreasing

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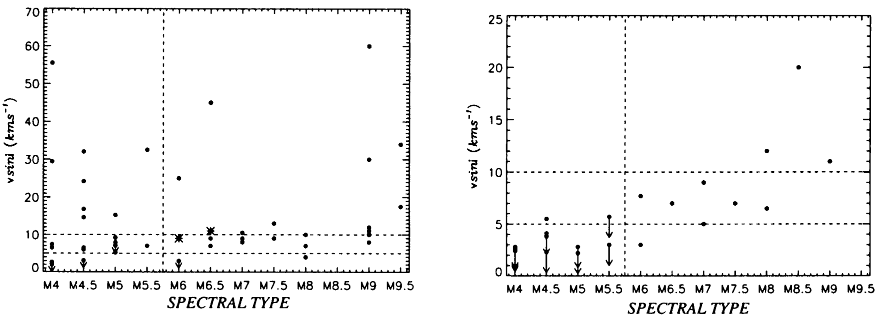

Figure 1. $v \sin i$ vs. spectral type for an age-biased M dwarf sample. a) The mid-M dwarfs include only those with young disk ages. The late M's include those with young disk, intermediate, or undetermined ages. No distinction is apparent in the distribution of $v \sin i$ between the mid- and late M's. b) Only old disk or halo stars are included. $v \sin i$ increases sharply with later type: most of the mid-M's have only upper limits in $v \sin i$, while all the late M dwarfs are detected, and all but one are moderate to fast rotators.

surface fluxes), so that this result was remarkable indeed. The object was re-observed the next year, but still showed no emission. The possibility of super-saturation was considered, but in any case it was clear that something new was going on.

Over the next few years, many more cool field objects were observed for rotation and activity : Basri (1996), Martín (1996, 1998), Tinney & Reid (1998), Delfosse et al. (1998), Basri (2000), Reid et al. (2002), Mohanty & Basri (2002). Other papers filled in the situation on activity (without measuring rotation) : Hawley et al (1996), Gizis et al. (2000), and coronal studies like Fleming et al. (1995). This work confirmed the initial impression that stellar activity makes a qualitative change at the bottom of the main sequence. The surface flux in Hα emission plunges, and is gone with very stringent upper limits in many of the L dwarfs. At the same time, the average rotational speed of the objects increases dramatically. The two are obviously related, since the spindown of hotter stars is mediated by angular momentum loss through a magnetic wind whose ultimate driving source is the corona. I do not review here the substantial literature on M stars in open clusters, which also helped with the overall context (especially for young ages).

The incidence of Hα emission is low in early M stars, and most of them are very slow rotators (Delfosse et al 1998). Its observed frequency increases into the mid-M stars, partly because of the increasing ease of producing emission against the fading photospheric brightness at 656nm, and partly because the number of measurably rotating stars begins to increase (Delfosse et al). Essentially all the M6 stars display Hα emission (Gizis et al. 2000), then the fraction decreases again towards M9. Both the numbers of rapid rotators and the velocities they achieve increase in the late M stars, and there are essentially no slow rotators among the L dwarfs (Basri 2000). Mohanty & Basri (2002) have considered whether the rotational behavior is due primarily to the spindown times increasing as the effective temperature decreases. Figure 1 shows their results using kinematic ages to try to sort this out. The question is a bit subtle because one must try to sort out age effects among the samples (it is easier to find younger objects among very low mass stars and brown dwarfs). Among the "young" sample there is a mixture of moderate and fast rotators (this may be due to the mixture of ages actually present), but in the "old" sample there is a clear tendency for the rotation to go up as the temperature goes down. This does indeed suggest that spindown times are much longer at the end of the M sequence than in its middle (and the same holds for L dwarfs, though that sample is even more likely to be biased towards young objects).

2.1. The Nature of the Rotation-Activity Connection

To examine the behavior of activity in late M stars, we must first convert Hα equivalent widths into an activity diagnostic that is more physical. Mohanty & Basri examine both the surface flux and ratio with bolometric luminosity. They yield qualitatively similar results (the effects are generally more dramatic in flux than ratio). To convert equivalent width to physical units requires a model atmosphere (or knowledge of the angular diameters); we use the models of Allard et al. (2001). The surface flux corresponding to a given equivalent width decreases rapidly from mid-M coolward. It is therefore remarkable (and puzzling) that the observed equivalent widths tend to cluster within an order of magnitude throughout the M and L dwarfs, while the continuum decreases by almost a factor of 1000. This result leads to a decrease in $L_{H\alpha}/L_{bol}$ with spectral type. To study the decrease with effective temperature, a calibration between it and spectral type must be given. This is still an active subject, but Mohanty & Basri provide a simple up-to-date function for it. Using these calibrations, we get the result in Figure 2. There is a general decrease in $L_{H\alpha}/L_{bol}$ below 3200K, and a rather precipitous drop below 2400K. It is found that temperature is the strongest organizing principle for predicting what the activity level will be (rather than rotation). Nonetheless, there is a range of activities present at a given temperature (at least until activity seems to almost die altogether).

We can now ask whether rotation is still a relevant variable in predicting activity ($L_{H\alpha}/L_{bol}$) levels. The primary results are shown in Fig. 3. The results there can be summarized as follows. In the mid-M stars, there is still a strong influence of rotation. One can predict that if a star is not active, its rotation is slow. The primary form of the relation is one of "saturation". In the upper panel grey filled circles are M4-M5 dwarfs, black open circles are M5.5-6.5 dwarfs, and black filled symbols are M7-8.5 dwarfs (the filled squares are the two flaring stars, LHS 2243 and LHS 2397A). It shows the saturation level is similar to somewhat hotter stars (dropping about a factor of 2 between M4 and M8), and the saturation velocity seems to be increasing (from about 5 km s^{-1} to 10 km s^{-1}, see inset). That is, there are later M dwarfs with velocities between 5-10 km s^{-1} which are not up to the saturation level, but all the earlier M dwarfs with those speeds are at saturation. Above 10 km s^{-1}, all the objects M4-M8.5 are at saturation levels. In the lower panel, the stars M8.5 and warmer are lumped together, and M9 and L objects are shown. Now something else is happening –

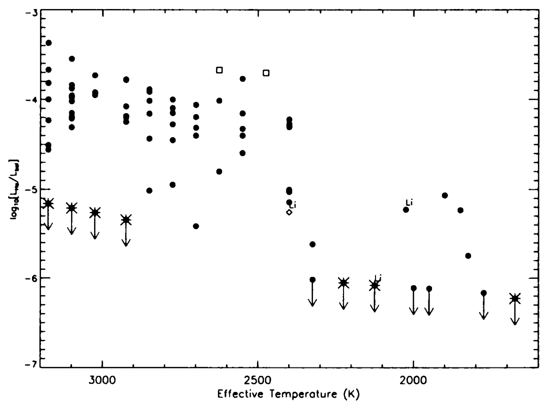

Figure 2. $L_{H\alpha}/L_{bol}$ vs. effective temperature. The squares mark stars which were probably flaring when observed. 'Li' indicates objects with detected Lithium; these are confirmed brown dwarfs (the diamond is LP 944-20). Arrows mark objects with only upper limits in Hα emission. Asterisks indicate that more than one object has been plotted.

the saturation level drops quickly at M9, and regardless how fast you spin an L star, it is hard to get any emission out of it.

The connection with rotation is broken, and temperature is a dominant characteristic which predicts the (lack of) activity. Mohanty & Basri have also examined whether the Rossby number is playing a role here, and conclude that it is not. In particular, the decline in activity at the end of the M sequence is not due to a super-saturation phenomenon (even though the stars are rotating faster and have very small Rossby numbers); the diagram does not organize itself when Rossby number is used, while it does when temperature is used. Reid et al (2002) do not even see a saturation effect in the late M stars, but Mohanty & Basri (2002) argue this is because of how they calculate the activity levels (which introduces extra scatter).

Meyer & Meyer-Hofmeister (1999) were the first to work out the basic argument that the increasing neutrality of the atmospheres at the end of the M sequence and into the L dwarfs might decouple the magnetic fields from the atmospheric motions and thereby lead to a decrease in the heating which leads to "activity". Their paper was concerned with the period gap in cataclysmic variables, but has direct application to the problem at hand. Mohanty et al. (2002) discuss the situation for L dwarfs more directly using the models of Allard et al. (2001). They show that in the relevant part of the atmosphere: the top of the convection zone (above which there may not be any motions to couple with anyway), the magnetic Reynolds number is too small in the L dwarfs and late M stars to allow the field to generate much of a non-potential component. They use reasonable velocities (between the convective eddy speeds and the sound speed), and find that the scale lengths required to generate a reasonable perturbed field (which could then be dissipated and heat the atmosphere) are very long. A

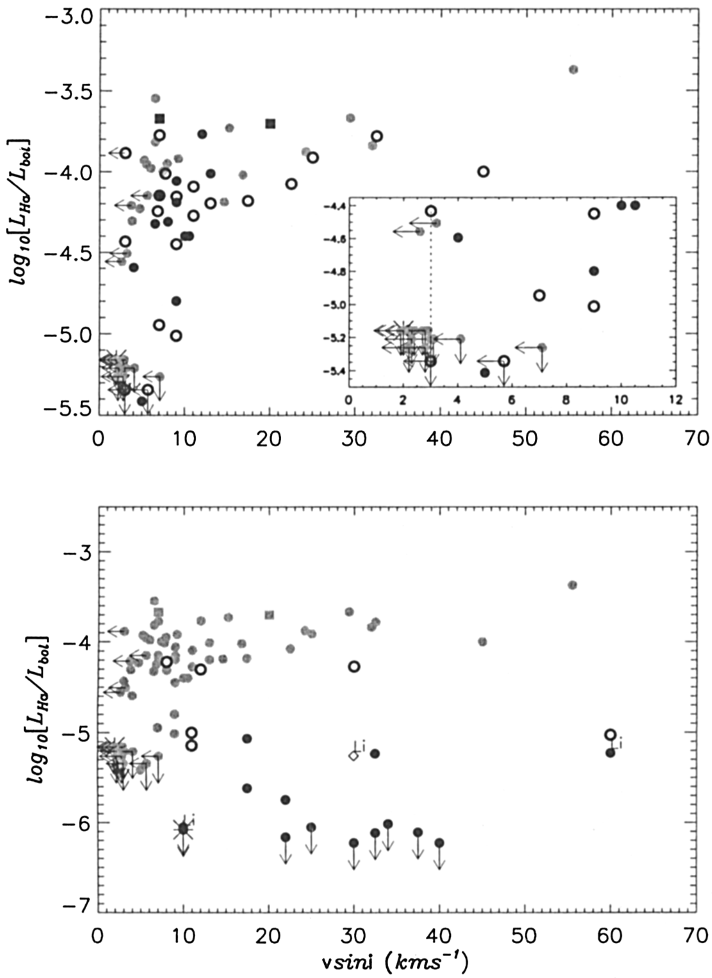

Figure 3. $L_{H\alpha}/L_{bol}$ vs. $v \sin i$. (from Mohanty & Basri 2000) *Top Panel*: M4 - M8.5 (symbols explained in text). The inset shows a close-up of the unsaturated dwarfs, with the vertical line at 3 km s^{-1} marking the cutoff velocity for saturation in M5 and earlier dwarfs. *Bottom panel*: Our entire sample down to L6. Grey symbols now denote M4-M8.5 dwarfs, black open symbols are M9 dwarfs (the open diamond is LP 944-20), and black filled circles are M9.5 and L dwarfs.

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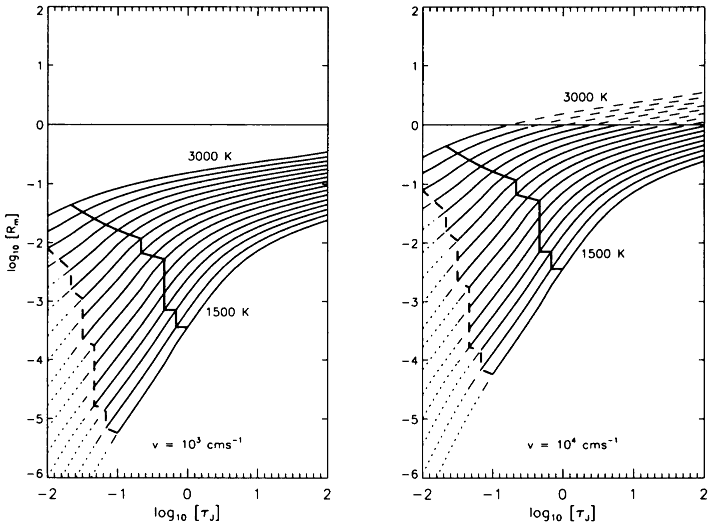

Figure 4. Magnetic Reynolds number as a function of J-band optical depth for T_{eff} = 1500 - 3000 K. The panels reflect different assumed gas velocities. The solid horizontal line indicates where δB becomes comparable to the background field B_0. Regimes where δB exceeds B_0 are shown by dashed lines. The upper limit of convection according to the models is shown by the thick solid curve and the thick dashed curve denotes possible convective overshoot. Dotted lines are regions where no convective motions are actually expected.

sample set of Reynolds numbers as a function of atmospheric depth are shown in Fig. 4. The clear conclusion is that atmospheric neutrality is an attractive explanation for the decrease in activity regardless of rotation at M9 and cooler.

2.2. Some Remaining Mysteries

In 1999, Reid et al. published "Another Surprise at the Bottom of the Main Sequence". When they observed BRI 0021-0214, the object that started this subject off by displaying no Hα emission, it turned up with a respectable emission line. Indeed, the flaring that they saw was suggested to occur in general between 5-10% of the time in late M stars. Other flares had been observed on slightly warmer stars like VB10 (M8; Linsky et al. 1995; Fleming et al. 2000). Subsequently there have been increasing numbers of detections of flares on very late M stars (e.g.,. Martín & Ardila 2001). An early Chandra observation of a nearby brown dwarf (LP 944-20) which was intended to show that the quiescent corona lies below very small upper limits (which it does), also showed that even without evidence of the corona (and a very small $L_{H\alpha}/L_{bol}$), the object mustered a respectable X-ray flare (Rutledge et al. 2000). This must mean that there is a substantial quiescent magnetic field present, which can sometimes and somehow be forced into a dissipative configuration. Even more surprisingly, LP 944-20 was joined by a number of other very low mass objects in exhibiting fairly frequent radio flares, with far more radio flux than would be expected from their Hα or X-ray power. It seems likely that a new type of flaring is being seen, with a currently unknown mechanism behind it.

Chandra and Newton (as did ROSAT) detect X-ray emission from brown dwarfs in star-forming regions (Comerón et al. 2000). The Hα emission is also generally stronger there (after disregarding cases of active accretion). It is seems that very young brown dwarfs have more activity at a given temperature and rotation than older ones. If neutrality is the only factor, can these be explained? One factor that must be explored is the lower gravity. At a given temperature it will allow more ionization, and the diffusion coefficients are also more favorable at lower densities. It is not obvious, however, that these effects are strong enough. Another possibility is that there is a primordial component to the field that is playing a role. This will be an interesting area for new investigations. The study of rotation and activity in brown dwarfs is clearly a fruitful and interesting new area of study.

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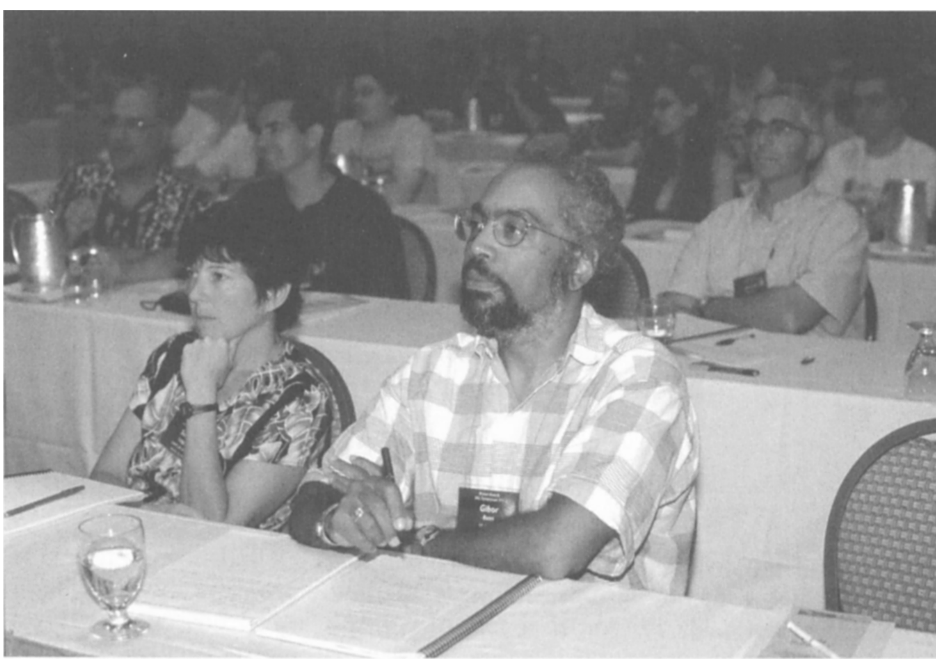

Sandy Leggett (*foreground, left*) and Gibor Basri

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