Stellar Rotation
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Rotation and Magnetic Activity in Brown Dwarfs

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Abstract. Brown dwarfs and very low mass (VLM) stars are the last frontier on the map of the angular momentum histories of star-like objects. Until the advent of 8-m class telescopes, it was impossible to obtain spectra with enough resolution to detect their rotation. The very existence of brown dwarfs was only established then. It was immediately apparent that there are differences between VLM objects and their heftier stellar cousins. Field VLM objects were found to be very rapidly rotating, yet they did not display the strong magnetic activity that would be expected of convective objects in that case. We now have a good preliminary understanding of the situation near the substellar boundary. I summarize the rotational data (both spectroscopic and photometric) on VLM objects, and how rotation and temperature fit into the production of magnetic activty. I also report more recent work on VLM objects when they are very young. There is increasing evidence that they form much like stars, beginning (when they become visible) as relatively slow rotators for the most part, followed by spin-up as they contract. Their disk lifetimes may be shorter, and they are more magnetically active when they are young. The subsequent angular momentum history of VLM objects is different from solar-type stars, as the usual magnetic braking mechanisms do not operate as in the stellar case. Much of the new work reported here is from the thesis of Subanjoy Mohanty, and was supported by NSF/AST-0098468.

1. Introduction

In this introduction, I will summarize what is known about the rotation of objects near the substellar boundary. Because the rotation of convective stars is closely related to their magnetic activity (and the other way around), I will interleave discussion of that. The body of this paper will then provide the observational backup for what I have said here.

There is ample discussion in this volume of the various angular momentum histories that stars of different masses may undergo. Of interest here is the behavior of stars with outer convection zones (solar-type stars), and particularly those which are fully convective throughout their lives (as occurs below about 0.25 solar masses). There is a large dispersion in the initial rotation rates of stars less massive than the Sun (see contribution by Mathieu), although a surprising number of them are found far below breakup, even as they are finishing the phase of accreting their mass. One hypothesis to explain this is "disk-locking" (which is also amply discussed elsewhere in this volume). Whatever the cause, many pre-main sequence stars rotate with periods of a week or more. Some however, rotate substantially faster even at this early time (and a few low mass cases have been found at a substantial fraction of the breakup velocity).

After the accretion phase, stars contract towards the main sequence. Initially the stars are fully convective, and appear at the "birthline" while burning deuterium. They contract down the Hayashi track while fully convective. Stars near one solar mass (which henceforth will be called "massive") then begin developing a radiative core, whereas VLM objects remain fully convective. If there is core decoupling at higher masses, one might expect the spindown rates to be faster than for stars that must accomplish it throughout their bulk. Of course, the contraction timescales also increase as the mass decreases. The contraction phase ends for solar-type and VLM stars when they reach the main sequence, and they tend to arrive as relatively rapid rotators. This generates copious dynamo activity and magnetic fields (continuing their high activity from the pre-main sequence). As a consequence, there are strong (even saturated) coronae, and relatively rapid magnetic braking of the stars through thermal magnetized outflow (a "solar wind") and coronal mass ejections. The stars are observed to spin down on the timescale of a few hundred million years; more massive stars spin down more rapidly (see the contribution by Stauffer in this volume).

Brown dwarfs follow a somewhat different course. Prior to their main contraction, they are held up for a while by deuterium fusion (one might call this a short "deuterium main sequence"). By definition, they never reach the hydrogen-burning main sequence, but their contraction is greatly slowed after a while by the developing degeneracy of the interior. They too exhibit fairly strong activity while young (the first few tens of millions of years), but in essence they just continue dropping down the Hayashi track. As they get older, cooler, and fainter, the levels of magnetic activity also drop. The activity must typically end during the contraction phase, because older brown dwarfs are almost all still rapidly rotating, and may never spin down. A typical field brown dwarf may have a rotation period of a few hours (reminiscent of Jupiter). Most of the brown dwarfs whose rotations have been studied to date are probably not much over a billion years old; the older brown dwarfs are so faint and cool that we have not yet been able to examine their spectra at high resolution.

2. Measurement of Rotation in VLM Objects

The primary means of measuring rotation for VLM objects is the same as for most of the other objects in this volume: $v \sin i$. The methodology is very similar as well. I note that in some ways these objects are very well suited for the measurement of spectral line broadening, since their velocities are not as high as for the massive stars, and their spectra are so full of molecular spectral lines that there is no continuum at all (so one should refer to the pseudo-continuum; although I will not continue with this distinction). The process entails directly comparing target spectra with standard spectra rotated computationally to a grid of velocities.

Ideally, the standard spectra should contain no intrinsic rotation themselves. One can make the comparison with rotational standards either using spectral line fitting (and finding the most similar case by eye or by a chi-squared fitting technique). Alternatively (and this is my preference) one can compare cross-correlation functions obtained by using the un-rotated standard as the template, and correlating it with the grid of rotated standard spectra and then the target spectrum. The width of the correlation function increases with $v \sin i$, and one can fit a function to this relation. The widths themselves can be found by Gaussian fitting to the correlation peaks (although in practice one does not always get peaks which have a Gaussian shape). This has a number of advantages, especially the fact that it works at fairly poor S/N (since a lot of information is averaged together). In echelle spectra one can make these determinations for each spectral order, and then average them (throwing out clear problems), or one can average the cross-correlation functions before fitting them. One hazard is the presence of telluric absorption lines (which are narrow), especially in the red where most spectra of cool objects are taken. One can de-select problematic spectral regions beforehand, or throw out anomalous correlation functions afterwards.

One of the main concerns in obtaining proper velocities is the choice of rotational standards. Although using standards which are different from the target by a few subclasses is generally feasible, the closer the match in spectral type the better. There is a lower limit to the rotational broadening that can be measured in standards, set by the resolution of the spectrograph and the other intrinsic sources of line broadening. In most cases, we are unable to measure $v \sin i$ of less than 2 km/s (and often 3 km/s). One issue is finding a standard that contains no rotational broadening itself. If it has some broadening itself. Early M stars are typically rotating slower than these limits, so many of them can serve as good standards. Targets with similar broadening will need to be rotating somewhat faster before their additional rotation can be discerned. If one knows in advance what the speed of the standard is, this can be accounted for to some extent, but objects only a little faster will not be measured properly. If one doesn't know the standards true speed, objects similar in speed will be counted as not rotating.

It becomes increasingly more difficult to find slow rotators as one goes to later spectral types. Basri et al. (2000) discuss the question of how to calibrate velocities if the standard has a substantial rotation (like 10 km/s). Of course, one first has to know whether the slowest star in the sample exhibits a measurable $v \sin i$. This was accomplished by stepping from early to late M stars, using standards a few subclasses earlier. We then performed a number of experiments using spun-up versions of Gl 406 (M6), to see how the inferred rotation depends on the velocity of the rotational template. We found that there are corrections of a few km/s if the target is only a few km/s faster than the template, but as the target is more than 5–7 km/s faster, these corrections diminish. Gl 406 is not a suitable template for L dwarfs, whose spectra are quite different due to the disappearance of TiO (hence the need for a different spectral classification). Most of the very late M and L stars we studied were substantially faster than our template 2MASS 1439+1929 (L1), which has the slowest $v \sin i$ we found (10 km/s). Corrections of less than 5 km/s were needed for targets with $v \sin i$ less than 30 km/s (diminishing as the speed goes up), and none is needed above 30 km/s. An alternative approach is to use spectra from model atmospheres calculations (which truly are not rotating) as the templates. The models are becoming increasingly good, even into the L dwarfs, and this is certainly a practical alternative earlier than mid-M.

When one studies very young VLM objects, another subtle problem appears. These objects are still in their main contraction phase (MCP; pre-main sequence is technically incorrect for substellar objects). As a result, their surface gravities are different than for field objects of the same spectral type (and the translation of spectral type to effective temperature is also different). The line widths in dwarf and giant stars of late M spectral types differ, with the molecular lines being broader by a substantial amount in giants compared to dwarfs (and the opposite of the narrower atomic lines seen in warmer giants). This is not likely to be due to rotation. When trying to come up with spectral standards for MCP VLM objects, White & Basri (2003) found it best to use a combination of giant and dwarf spectra. For example, a composite (M7V + M7III) spectrum is a better fit to an M7 MCP object than either of the individual spectra. They used the same procedure for producing a rotational standard, which yields $v \sin i$ values which are intermediate between the faster values found from dwarf standards and the slower values found from giant standards. The reason why giant's molecular lines are broader has not yet been explicated; White & Basri suggest as possibilities 1) a weakened continuum and enhanced molecular strength at lower gravity, 2) increased turbulence, or 3) reasons related to the temperature mis-match at the same spectral type. Detailed model atmospheres analysis will be needed to sort this out, but the effect is clearly there.

2.1. Photometric Variability

The other means of determining stellar rotation, especially among magnetically active stars, is through photometric variability. This relies on a sufficiently non-axisymmetric distribution of patches with different luminosities on the surface of the star to produce a periodic light curve (or at least a light curve with a periodic signal in it). Although it takes many more observations than a measurement of $v \sin i$ (which only requires a single spectrum), the observations can be made with a smaller telescope and simple camera. There is the further great advantage that one obtains a true rotation period (not subject to an unknown inclination as with $v \sin i$). This can be converted to a rotational velocity if the stellar radius is known (although sometimes the period itself is a more desirable result).

When Basri & Marcy (1995) found surprisingly rapid rotation (at least 20 times faster than typical early M stars) in BRI 0021 (M9.5), efforts began to measure the predicted rotation periods, which are only a few hours. Since they had also found no magnetic activity on BRI 0021, it was not clear there would be any modulated signal from these objects. Martín, Zapatero-Osorio & Rebolo (1996) reported low-level variability (a few percent) but the expected short periods in the first few late-M stars. Since then, a number of groups (eg. Clarke, Tinney & Covey 2002) have found similar results (although many objects are not variable at this level) . It may be easier to find such variations in young objects (eg. Terndrup et al. 1999). Similar studies have been extended down into the L dwarfs (Gelino et al. 2002). In addition to short-term period variations, longer-term (few day) non-periodic variability has also been seen (Martín, Zapatero-Osorio & Lehto 2001). As we will see below, one does not necessarily expect magnetic spotting in L dwarfs. Instead, we may sometimes be seeing light variations due to patchy dust clouds in the atmospheres of these very cool objects, and the longer term variability may correspond to "weather" rather than rotational variability.

3. Results on the Rotation of VLM Objects

Marcy & Benitz (1989) found that very few early M stars were rotating at more than 5 km/s (and those are dMe stars, and clearly quite young). Delfosse et al. (1998) extended our knowledge of the rotation of early and mid M stars, showing that the fraction of rapid rotators begins to rise as one moves cooler. They found that none of the older stars hotter than M5–6 had measureable rotation, and even the young disk stars hotter than M3.5 are largely spun down. They interpreted these results as implying that spindown times increase as the mass decreases for low mass stars. By the time one comes to the cool end of the M spectral class, there are very few slow rotators. That this might be true was first suspected by Basri & Marcy (1995) as mentioned above. Basri et al. (1996) established (with 18 measured rotations) that this was not a fluke, and by the end of the decade it was very clear that rapid rotation is the rule rather than the exception at the bottom of the main sequence (Tinney & Reid 1998; Basri 2000).

Reid et al. (2002) conducted a new study of rotation in 23 late M stars. Their sample is purely photometrically selected (specifically to avoid a bias to older objects found by high proper motion). They find that "the relative number of fast ($v \sin i > 20$ km/s) and slow rotators is invariant with spectral type, although there is marginal evidence that the average rotational velocity of M9/9.5 dwarfs is higher than among earlier types." Mohanty & Basri (2003) measured and compiled a large list (65) of rotation velocities in very cool objects, including a number of stars selected by proper motion. In their overall sample (which extends well into the L spectral class) the fraction (and average speed) of rapid rotators increases smoothly as the effective temperature decreases. None of the L dwarfs is rotating at less than 10 km/s. Figure 1 is from this work (it includes some of the objects in Reid et al.). Quite obviously, there is a tendency for very cool objects to be rapid rotators, and the trend increases as temperature decreases in the later half of the M sequence and beyond.

Less obvious is whether this directly translates to increasing spindown times. As one crosses into the L dwarfs, the fraction of brown dwarfs is increasing, and cooler than L3 or so it reaches 100%. This means that there is a strong bias towards younger objects, since a given brown dwarf will traverse all these spectral types as it cools, and actually spends most of its time as a T dwarf (becoming so faint that there is no information on their rotational properties yet). One can worry to what extent the fact that all the L dwarfs are rapid rotators is more a result of their youth than their spindown times. Mohanty & Basri (2003) separate their sample of M dwarfs into kinematically young in one case, and kinematically old or unknown kinematics in the second case. They concur in the conclusion of Reid et al. for the young sample – that there is a mix of fast and slow rotators. In the old sample of M dwarfs, however (which were preferentially missing in the Reid et al. sample), the trend of increasing rotation with decreasing temperature is quite apparent. Thus, it seems reasonable to

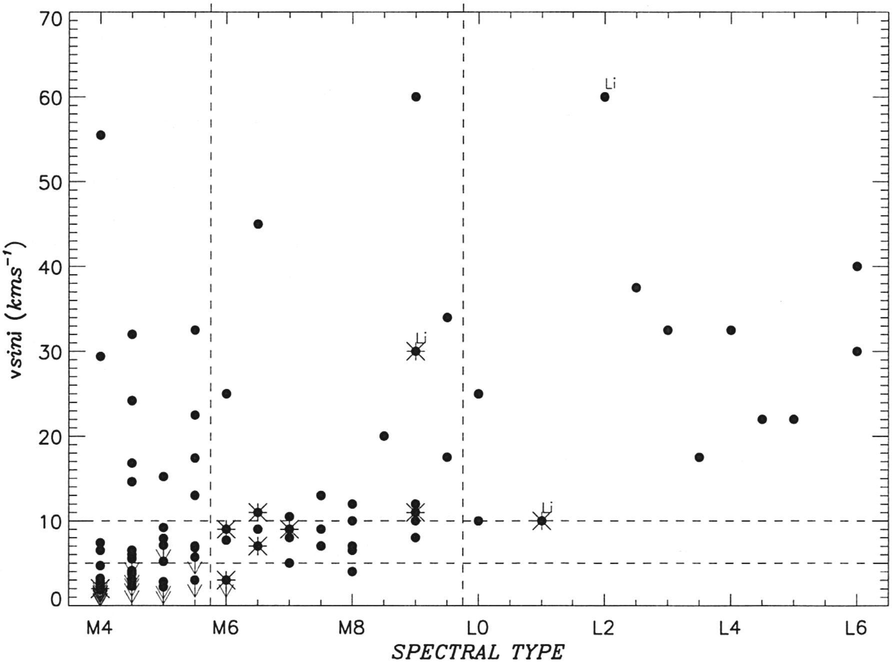

Figure 1. Figure 1. Rotation versus spectral type in field objects. Most of the mid-M dwarfs are slow rotators, many with only upper limits in $v \sin i$ (the actual number of these is much larger than apparent, due to superposition). None of the stars leftward of the first vertical line are both kinematically old and above 10 km/s (in fact almost all old stars are below 5 km/s), while none rightward of the second vertical line are below 10 km/s. Arrows mark stars with only an upper limit in $v \sin i$. Asterisks mark positions where two or more stars are superimposed. 'Li' marks stars with detected Lithium. See Mohanty & Basri (2003) for more details.

suppose that in fact very cool objects have very long spindown times (we shall see below that it would not be surprising if there were no spindown at all once an object is an L dwarf).

4. Magnetic Activity

Kraft (1967) was one of the first to notice the strong division between really massive stars with radiative exteriors (which remain rapid rotators) and solar-type stars (which are typically slow rotators in the field). He also noted that more rapidly rotating solar-type stars tended to show more CaII emission (and therefore magnetic activity) and correctly surmised that because there is good evidence these stars are younger, magnetic winds must spin down convective stars until they end up slowly rotating and inactive. It is a little scary to think that not much else has been added to our conceptual framework of the angular momentum history of main-sequence convective stars since then (although a great many details have been filled in, and we now understand the earlier phases much better). Today we are firmly convinced that rotation and activity are strongly correlated (Noyes et al. 1984). This arises as a result of rotationally-dependent dynamo production of the magnetic fields whose dissipation is responsible for the non-radiative heating that is meant by 'activity'. There is a feedback between the strength of the activity and the magnetic braking which ultimately decreases the rotation, and therefore the activity. If we understand the rate at which this occurs, one can use activity levels as an age indicator (and indeed this is the primary means other than kinematics for assigning ages to field main sequence solar-type stars). The 'Skumanich Law' is generally applied (Skumanich 1972). Gray (1982) suggested that this mechanism may leave all convective stars of a given mass rotating at the same final rate late in their main sequence tenure.

This comfortable and very successful paradigm suddenly fell apart when rotation and activity were studied in VLM objects. As mentioned above, observations of BRI 0021 made it clear from the start that the strong dependence of activity on rotation is completely inoperative for that object. In fact, the nature of the relation changes somewhat at earlier M subclasses. Rotation still matters, but primarily to produce a 'saturation velocity', faster than which stars exhibit the same high level of activity. That some change might occur is not entirely unexpected; the $\alpha - \omega$ dynamo that operates in solar-type stars relies on the shear layer between the outer convective and inner radiative zones. Cooler than about M3, the stars become fully convective, and the nature of the dynamo must change. A fully turbulent dynamo would perhaps not depend on rotation, but the saturation relation persists (with perhaps an increasing saturation velocity in later M stars). One possibility is that an $\alpha - \alpha$ dynamo is now operating. We have recently discussed these issues at IAU Symposium 211 (Basri & Mohanty 2002), and they are discussed in much greater detail in Mohanty & Basri (2003).

To quickly summarize, even the saturation relation disappears at around M9. Cooler than that, there seems to be no connection between rotation and activity. In fact, activity is quickly falling away (as very nicely shown by Gizis et al. 2000), while rotation is rapidly increasing (Basri 2000). The most obvious explanation is that somehow stellar activity is no longer generated by rotation, and therefore magnetic braking is also turned off. This could in principle be due either to a cessation in the production of magnetic fields, or a mechanism which prevents the dissipation of the fields. If non-radiative heating does not occur, a corona is not produced and the Parker (thermal) wind which drives magnetic braking cannot occur. Because it turns out there is still occasional flaring on some of these stars (Berger 2002), it appears that a field is still present. The best explanation, therefore, is that magnetic dissipation is inhibited. The theory behind that concept has been worked out in some detail by Mohanty et al. (2002). As atmospheres become very neutral, their conductivity falls so low that charged particles (ions or electrons) cannot be frozen to field lines and are easily swept off by the huge population of neutrals. Atmospheric motions, therefore, cannot twist the field into non-potential configurations, and currents and reconnection are no longer supported. This appears to be the reason that rotation rates remain high in very cool objects, and suggests there is almost no further magnetic braking when objects cool below the M spectral class. The presence of flares is still puzzling; until we understand how they are generated we cannot be sure there is no braking at all.

5. Young VLM Objects

The final question to consider is how VLM objects start off in their angular momentum history, and what happens when they are young. The two main differences in their youthful stages is that they are indeed more magnetically active, and they begin relatively large, then undergo contraction. There are competing ideas of how these objects form, but it is a virtual certainty that they form within a circumstellar accretion disk. Muzerolle et al. (2000) and White & Basri (2003) have presented rather direct evidence that during the accretion phase these objects resemble classical T Tauri stars. Early on, the disk fraction around VLM objects is fairly high (Meunch et al. 2001; Natta et al. 2002), but there is evidence that the disk fraction falls more rapidly than for T Tauri stars (Jayawardana, Mohanty & Basri 2002; White & Basri 2003). It does not matter much whether the objects form mostly on their own, or are ejected from multiple (small-N cluster) systems, so long as they have a disk during their main accretion phase (as they seem to).

When the majority of very young stars seem to initially be relatively slow rotators (well below breakup), one tends to think in terms of a mechanism that either removes angular momentum very efficiently during accretion (which in principle might spin the star up close to breakup), or a mechanism which prevents the angular momentum from reaching the star (while mass does). The disk-locking scenario is one such mechanism, which is discussed at some length elsewhere in this volume. Here, I just present evidence that VLM objects begin as relatively slow rotators (resembling classical T Tauri stars), and already show signs of spinning up after a few million years. The deuterium main sequence lasts for 3–5 million years for high mass brown dwarfs, less than that for VLM stars, and up to 20 million years for low mass brown dwarfs. After that, the main contraction phase ensues, and lasts a similar amount of time.

We have been studying VLM objects in star-forming regions using high-resolution spectroscopy. The first results are for Upper Scorpius (5 million yr old; Jayawardana et al. 2002) and Taurus-Auriga (2–3 million yr old; White & Basri 2003). I include here unpublished results from our recent run on IC 348 (2–4 million yr old). The ages of Taurus and IC348 are similar, but the disk fraction in IC348 may favor a slightly older age (although there could be intrinsic differences from region to region). We have measured rotations for over 10 stars in each cluster, and the results are shown in Figure 2. Taurus contains the slowest rotators (with almost all in the neighborhood of 10 km/s), IC 348 has an intermediate population (more in the neighborhood of 20 km/s, and a couple of cool rapid rotators), and Upper Sco is similar (the 3 rapid rotators are warmer). It is a bit odd that the rapid rotators in IC348 are cool, as their contraction should not be as far along. Of course, one always sees a mix of rotations (corresponding both to initial conditions and perhaps differences in disk lifetimes). In truth, we neither have enough statistics to draw firm conclusions, nor do we know whether age or intrinsic differences play a bigger role. The average velocities in the three regions are consistent with a spinup as contraction occurs (most of our objects are either VLM stars or high mass brown dwarfs), for what it is worth.

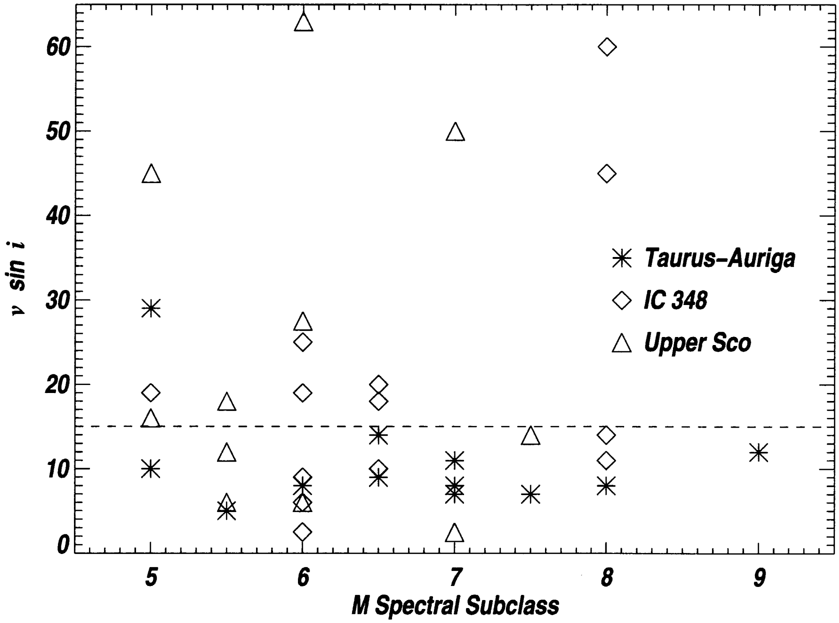

Figure 2. Figure 2. Rotation versus spectral type in star-forming regions. Each symbol stands for a cluster with a different very young age. The dashed line is at 15 km/s; an arbitrary dividing line between slow and faster rotators. There is a possible tendency for older objects to be rotating more quickly on average (at any rate, Taurus has the slowest rotators of the three, and Upper Sco is the oldest).

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