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Angular momentum and disk evolution in very low mass systems

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Abstract. This review summarises recent observational results regarding the evolution of angular momentum and disks in brown dwarfs. The observations clearly show that brown dwarfs beyond ages of 10 Myr are exclusively fast rotators and do not spin down with age. This suggests that rotational braking by magnetic winds becomes very inefficient or ceases to work in the substellar regime. There is, however, some evidence for braking by disks during the first few Myrs in the evolution, similar to stars. Brown dwarf disks turn out to be scaled down versions of circumstellar disks, with dust settling, grain growth, and in some cases cleared out inner regions. The global disk properties roughly scale with central object mass. The evolutionary timescales in substellar disks are entirely consistent with what is found for stars, which may be challenging to understand. Given these findings, it is likely that brown dwarfs are able to form miniature planetary systems.

1. Introduction

Angular momentum and disk evolution are rarely combined in a review, but these two topics are fundamentally related to each other. The disk controls the early angular momentum evolution of stars. Many aspects in the evolution of disks, including those relevant for planet formation, are related to the angular momentum transport in the disks and thus have an indirect connection to the rotation of the central objects. It is now established that the rotation of young stars is regulated by interaction with their disks ('disk braking').

The emphasis of this review, however, are observational results. Apart from the disk braking mentioned above, there are very few direct observational links between rotation and disks. This is even more so in the substellar regime, where studies are generally hampered by the faintness of the sources. I will therefore treat these two subjects mostly separately.

I will focus on brown dwarfs, although some of the objects discussed below may turn out to be stars very close to the Hydrogen burning limit. Brown dwarfs are intriguing systems because they allow us to probe physical processes as a function of the object mass. Therefore, I will introduce the two main sections with a brief summary of the status of our understanding in solar-mass and low-mass stars. This can be used as a reference point to test the brown dwarf regime.

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2. Angular momentum evolution

The rotational evolution of low-mass stars can be divided in two distinct phases, which can also be used as a framework for interpreting the findings for brown dwarfs: (see reviews by Herbst et al. 2007; Scholz 2009)

(1) During the first few million years, the rotation is strongly regulated in the sense that angular momentum is not conserved and the period, averaged over a large sample, stays largely constant. This regulation is presumably due to some interaction between star and disk, in the following called disk braking.

(2) After the disks have disappeared, the rotational evolution is determined by the spin-up due to pre-main sequence and, on longer timescales, by angular momentum losses due to magnetically driven stellar winds. This causes the spin-down of solar-mass stars to rotation periods of weeks.

Rotation periods measured from inhomogeneously distributed surface features corotating with the objects are the ideal observational diagnostics of stellar and substellar rotation. The surface features can be magnetically induced spots or, as in ultracool dwarfs, patchy clouds. Although I will focus on periods, an assessment of the rotational evolution is also possible through measurements of spectroscopically determined rotational velocities which provide complementary information.

Six years ago, only about 30 rotation periods for brown dwarfs were known, see Fig. 6 in Herbst et al. (2007). In the last years, the period database has grown significantly, but it is still sparsely populated, particularly at ages > 10 Myr. More datapoints are needed at all ages to provide further constraints and to improve the statistics. In Fig. 1 we show the currently known periods for brown dwarfs, to illustrate the main trends and the currently existing samples. While the periods for very young objects (ages < 10 Myr) show a wide range, from several hours up to 20 days, the periods for older objects are all shorter than 1 day.

2.1. The evolved objects

The evolved objects in this plot with ages $>$ 10 Myr do not possess disks. Their rotational evolution is only affected by contraction and wind braking. As mentioned above, all periods for evolved brown dwarfs are shorter than 1 day. This is confirmed by the available spectroscopic data. The lower limit of the projected rotational velocities for ultracool dwarfs increases from mid M to L dwarfs, with the effect that all L and T dwarfs have $v \sin i$ larger than $7\,\mathrm{km\,s^{-1}}$, corresponding to periods shorter than 17 h (Reiners & Basri 2008, 2010; Blake et al. 2010; Konopacky et al. 2012).

Thus, the observations show very convincingly that all evolved brown dwarfs are fast rotators. This can only mean that wind braking becomes extremely inefficient in the substellar regime or even ceases to work. This continues a trend that has been noticed in the stellar regime by several groups: the spin-down timescale is a strong function of mass and increase towards lower mass objects. Stars with $0.3\,M_\odot$ need 0.5 Gyr to spin down[1] (Scholz et al. 2011). For $0.1\,M_\odot$ this timescale increases to several Gyr (Irwin et al. 2011). The observational data suggests that the rotational braking becomes gradually less efficient towards lower masses, until it essentially shuts down for brown dwarfs. Brown dwarfs might still spin down, but it could take more than the current age of the Universe. A slowly rotating brown dwarf would constitute a fossil object from the beginning of the Galaxy.

The transition from slowly rotating main sequence stars like the Sun to fast rotating brown dwarfs is remarkable, because it puts brown dwarfs in the regime of giant planets when their long-term rotational evolution is considered. Similar to giant planets and in stark contrast to stars, brown dwarfs do not spin down as they age and continue to be fast rotators. This also means that, in contrast to stars, coeval brown dwarfs with similar masses do not necessarily have similar rotation periods.

It is not clear yet what causes this breakdown of wind braking in the very low mass

[1] This assumes an exponential spin-down law with $P \propto \exp(t/\tau)$.

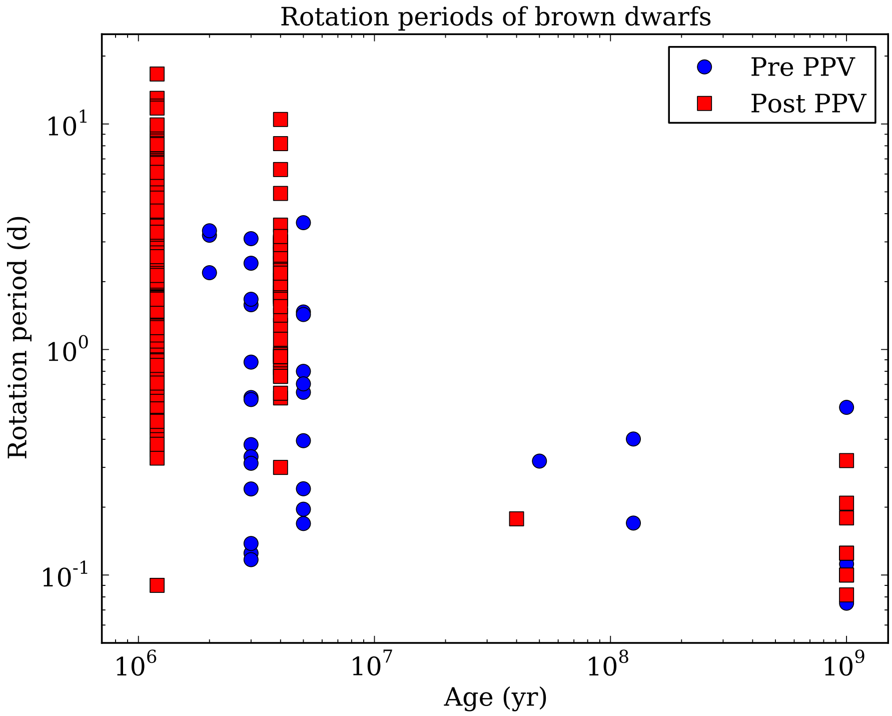

Fig. 1. Rotation periods of brown dwarfs. Periods published before and after the Protostars & Planets V review by Herbst et al. (2007) are shown in [blue] circles and [red] squares, respectively. Periods for ultracool field dwarfs with unknown age are plotted at 1 Gyr. The figure contains datapoints from: Martin & Zapatero Osorio (1997); Terndrup et al. (1999); Bailer-Jones & Mundt (2001); Clarke et al. (2002); Zapatero Osorio et al. (2003); Joergens et al. (2003); Scholz & Eislöffel (2004a,b); Caballero et al. (2004); Scholz & Eislöffel (2005) for 'Pre PPV' and Koen (2006); Lane et al. (2007); Rodríguez-Ledesma et al. (2009); Artigau et al. (2009); Scholz et al. (2009); Cody & Hillenbrand (2010); Radigan et al. (2012); Girardin et al. (2013); Heinze et al. (2013); Gillon et al. (2013) for 'Post PPV'.

regime. This fact has often be interpreted as a sign of a change in the magnetic field generating dynamo (e.g. Scholz 2004), but this is unlikely to be the only cause (see Scholz et al. 2009). Changes in magnetic field topology could also play a role (Morin et al. 2010). Furthermore, as argued by Reiners & Mohanty (2012), adopting a modified spin-down law with a retained dependence on the radius could explain this transition without any further changes in the physics. Independent observations of magnetic field indicators as well as further critical evaluation of the theory are important steps to answer this question.

2.2. The young objects

The rotation periods for young objects provide information on the initial angular momentum content of brown dwarfs. The periods exhibit a large scatter, from fractions of a day up to 10 days, with a tail to even longer periods. While the total spread in periods is similar to more massive stars, the period distribution is not. In all these samples there is a consistent trend of 'faster rotators lying towards lower masses' (Rodríguez-Ledesma et al. 2009). In the Orion Nebula Cluster (ONC), the median period drops from 5 d for $M > 0.4\,M_{\odot}$ to 2.6 d for very low mass (VLM) stars and to

2 d for brown dwarfs. Thus, there is a clear mass dependence in the rotation periods at very young ages. As noted by Cody & Hillenbrand (2010, their Fig. 10) and earlier by Herbst et al. (2001), this period-mass trend is consistent with specific angular momentum being independent of object mass. This equipartition of angular momentum is an interesting outcome of the star formation process and could provide a useful constraint on theories for collapse and fragmentation of clouds.

A controversial aspect of the brown dwarf periods in star forming regions is their lower limit. The breakup limit, where centrifugal forces are in balance with gravity, is between 3 and 5 h at these young ages. Zapatero Osorio et al. (2003), Caballero et al. (2004), and Scholz & Eislöffel (2004a, 2005) report brown dwarf periods that are very close to that limit. On the other hand, the Cody & Hillenbrand sample contains only one period shorter than 14 h, although their sensitivity increases towards shorter periods. It remains to be confirmed whether some young brown dwarfs indeed rotate close to breakup or not. This is an important point to clarify, as rotation near breakup would be expected to have a substantial effect on interior structure, evolution, and angular momentum control for these objects.

Several groups have searched for a relation between rotation and the presence of disks in the VLM regime, to probe for the existence of disk braking. The evidence is ambiguous. The data presented in Cody & Hillenbrand (2010) for the σ Ori cluster 'do not support a direct connection between rotation and the presence of a disk', but their sample may be too small for a definite statement. Moreover, their Fig. 15 does seem to show that fast rotators are mostly diskless, in line with the expectation for disk braking. For another small sample in the same cluster, Scholz & Eislöffel (2004a) find tentative evidence for a a disk braking scenario.

For the much larger sample in the ONC, Rodríguez-Ledesma et al. (2010) find that objects with near-infrared excess tend to rotate slower than objects without NIR excess in the mass regime between 0.075 and 0.4 $M_\odot$. This is interpreted as evidence for disk braking. No such signature is seen in the substellar regime. One possible caveat here is that many brown dwarf disks show little or no excess emission in the near-infrared and require mid-infrared data to be clearly detected. Lamm et al. (2005) show clear signs of disk braking for the VLM stars in NGC2264, but also suggest that disk braking becomes less efficient in the VLM regime. Finally, for a diverse sample of young very low mass stars and brown dwarfs, Mohanty et al. (2005) show that objects undergoing disk accretion are clearly seen to be preferentially slow rotators.

Combining all these studies, we conclude that some form of disk braking seems to operate into the VLM regime and possibly in brown dwarfs as well. At least, there is no strong evidence against this possibility. However, the exact mass dependence of this process remains to be clarified. This requires to either obtain sensitive mid-infrared data for a large sample of objects with known period or, conversely, periods for objects with known infrared spectral energy distribution (SED).

2.3. Summary

The aforementioned findings can be summarised in a very concise form: In brown dwarfs, some form of disk braking seems to be at work, but wind braking is not.

3. Disk evolution

Disks are relevant for a number of relatively obvious reasons. First, they are the matter and angular momentum reservoir of forming stars and thus may have an effect on the final properties of stars and brown dwarfs. Second, global disk properties could theoretically contain a fossil record of events in the earliest evolutionary stages that are difficult to observe. And third, disks are the birth places of planets, their evolution thus establishes the boundary conditions for the architecture of planetary systems. It is the latter aspect that will dominate the following discussion. Brown dwarf disks allow us to test planet formation in an extreme regime, which provides constraints on the robustness of planet formation scenarios.

Our interpretation of observations of brown dwarf disks is informed by our understanding of disks around stars (for a recent review see Williams & Cieza 2011). In any given star-forming regions, three different types of dusty disks are observed: 1) strongly flared disks, 2) disks that are flatter presumably due to dust settling to the midplane, 3) disks with emission deficits in the near/mid-infrared, usually seen as signs for cleared out inner regions ('transition disks'). While it is tempting to see these three types as an evolutionary sequence, it is important to remember that we do not know whether all disks pass through these three stages, or not. Brown dwarf disks are useful environments to test processes like dust settling and inner disk clearing.

The first detections of dusty disks around brown dwarfs were published about 10-15 years ago, only very few years after the discovery of brown dwarfs (Comeron et al. 1998; Muench et al. 2001; Natta & Testi 2001; Testi et al. 2002). The prevalence of disks down to masses of 0.01 $M_\odot$ (Natta et al. 2002) and the general similarity of stellar and substellar disks was established already in these early stages (e.g. Jayawardhana et al. 2003; Liu et al. 2003; Mohanty et al. 2004), albeit often only with anecdotal evidence. The various infrared satellite missions of the recent years, in particular Spitzer, Herschel, and WISE have for the first time made studies of brown dwarf disks with meaningful samples feasible.

3.1. Disk lifetimes

In mid-infrared colours, there is usually a clear gap between objects with excess above the photosphere and those without, which means that the fraction of objects with disk can be readily derived. Disk fractions are robust as long as the underlying sample is sufficiently large and unbiased. Using this technique, it is now ascertained that the disk fractions do not drop substantially down to the lowest mass objects identified in star forming regions (e.g. Scholz & Jayawardhana 2008; Zapatero Osorio et al. 2007).

When the most recent studies with the largest samples are considered, the disk fractions in the brown dwarf regime are consistent with those for low-mass stars (K and M dwarfs) within the statistical limits. A good example is the star forming region Upper Scorpius, with an age of 5-10 Myr, an important benchmark test for the long-term evolution of disks. According to Dawson et al. (2013), its brown dwarf disk fraction is 23 ± 5% (Fig. 2), consistent with other recent estimates of this quantity (Lodieu 2013; Luhman & Mamajek 2012). For comparison, the disk fraction for K0-M5 stars is 19% (Carpenter et al. 2006). The disk fractions of low-mass stars and brown dwarfs in the younger regions Chamaeleon-I, IC348, and σ Ori appear very similar as well (see Fig. 2). This suggests that the overall disk lifetime in brown dwarf samples and the rate at which they lose their disks is not different from low-mass stars.

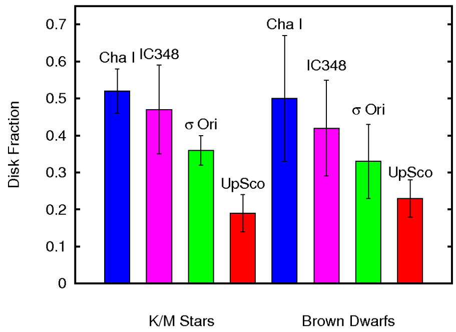

Fig. 2. Disk fractions for low-mass stars and brown dwarfs in various star forming regions, from Dawson et al. (2013). The figure contains results from Luhman et al. (2005); Lada et al. (2006); Hernández et al. (2007); Damjanov et al. (2007).

The fraction of transition disks among brown dwarf disks is again comparable to low-mass stars. For example, Dawson et al. (2013) determined it as 19% for Upper Scorpius, whereas values for low-mass stars are broadly in the 10-20% range (Ercolano et al. 2009; Muzerolle et al. 2010). The errors in these numbers are large due to the small sample size, in addition, transition disks are a diverse group of objects and the separation from 'normal' disks is often not unambiguous. The brown dwarf transition disk fraction translates to clearing timescales in the order of 0.4 Myr or less, again comparable to low-mass stars, suggesting that the clearing process is independent of the object mass and luminosity. This could be a serious challenge for scenarios where photoevaporation driven by the ultraviolet radiation from the central object is the physical process responsible for the clearing (e.g. Alexander et al. 2006). It follows that brown dwarf disks show a two-timescale evolution, with a long-term dissipation and a much faster inner disk clearing, mirroring the behaviour of disks around low-mass stars.

3.2. Dust settling

A comparison of the SEDs of brown dwarf disks in diverse regions shows that the median flux level drops with increasing age (Scholz et al. 2012). More specifically, the fraction of highly flared disks drops with age, and becomes negligible in the relatively old Upper Scorpius star forming region (Scholz et al. 2007). This evolutionary behaviour is best explained by dust settling to the midplane of the disk (see discussion in Scholz et al. 2009), a consequence of grain growth.

More evidence for grain growth in brown dwarf disks comes from the analysis of the silicate feature around 10 μm. Brown dwarfs feature broad, flat silicate feature, more so than T Tauri stars and Herbig stars, indicating an advanced stage of grain growth and grain removal from the upper layers of the inner disk (Apai et al. 2005; Scholz et al. 2007). This could simply be a result of the fact that this feature traces regions much closer to the object for cooler objects and the depletion of dust grains close to the central source is faster due to the enhanced collision rates, although other explanations are possible (Pascucci et al. 2009).

Whether the dust settling inferred from the mid-infrared SEDs and thus the growth of dust grains and the boundary conditions for the formation of rocky planets is a function of the mass of the central object remains unclear. Szűcs et al. (2010) analyse mid-infrared SEDs and show that there is a significant difference in the Spitzer/IRAC colour distributions of disks around low-mass and very-low mass stars. In both mass bins, a degree of dust settling (i.e. flattened disks) has to be assumed to explain the SEDs. However, as argued by Szűcs et al. (2010), 'relative to the disk structure predicted for flared disks, the required reduction in disk scale height is anti-correlated with the stellar mass'. In other words, disks around very low mass stars are flatter. This trend could continue into the brown dwarf regime.

A different approach with a different result was presented by Mulders & Dominik (2012). They model the SEDs of Herbig stars, T Tauri stars, and brown dwarfs in a self-consistent way, and find that 'regions with the same temperature have a self-similar vertical structure independent of stellar mass'. However, regions at the same distance from the central object appear more settled in brown dwarfs, due to their lower luminosities. Thus, the flatter disk structure of brown dwarfs are more a result of their lower luminosities than different physical processes in the disk evolution. The turbulent mixing strength, parameterised using the α prescription, is the same in all three samples. Thus, according to their analysis, disks around objects with a wide range of stellar and substellar masses have self-similar structures and provide similar environments for the early stages of rocky planet formation.

3.3. Submm/mm observations: the next frontier

For many outstanding problems in this field the crucial spectral domain is the submm/mm wavelength regime. At these wavelengths, the disks are mostly optically thin. As a result, the emission directly traces the properties of the bulk of the dust in the disk, including the total dust mass and the dust opacity. Also, submm/mm observations provide the best opportunity to resolve the disks and thus put limits on their physical dimensions.

The submm/mm domain remains the wavelength regime where our observational database is still very sparse. Only about a handful of brown dwarfs have been detected, using MAMBO-2 at IRAM, SCUBA and SCUBA-2 at JCMT as well as the SMA (Klein et al. 2003; Scholz et al. 2006; Bouy et al. 2008;

Phan-Bao et al. 2008; Mohanty et al. 2013). These results tentatively indicate that the substellar disk masses are around 0.5%, roughly comparable to T Tauri stars. For comparison, Harvey et al. (2012) report relative disk masses of a few 10^{-5} to 10^{-2} times the central object masses, which could indicate a drop in the relative disk masses compared with T Tauri stars. However, these results are based on Herschel/PACS far-infrared fluxes, insensitive to relatively cold and large dust grains and not in the optically thin regime. At this point it might be useful to consider these values lower limits when comparing with disk masses derived from submm/mm data.

The total radii of brown dwarf disks are very poorly constrained. Combining the result from the first resolved observations of a brown dwarf disk (Ricci et al. 2013) with some more indirect constraints (Luhman et al. 2007; Scholz et al. 2006), it seems that some brown dwarf disks have radii in the range of 10 to 40 AU, about a factor of ten smaller than the largest T Tauri disks.

Recently, Ricci et al. (2012) reported the first observations of a brown dwarf disk with the new submm/mm interferometer ALMA. The main result from this study is the detection of millimeter sized grains in the brown dwarf disk, with a spectral slope that is comparable to T Tauri stars. This is so far the clearest demonstration that grain growth is a very robust process that occurs even in the low-density environments of brown dwarf disks. The result also challenges the theory for grain growth. To stop the strong radial drift, Pinilla et al. (2013) suggest the presence of extreme pressure bumps in the dust distribution to trap the particles. Whether such a scenario is plausible, remains to be explored (see also the contribution by Ricci in these proceedings).

The 1 mm detection by Ricci et al. took only 15 min total integration time with ALMA and yielded a flux uncertainty of 0.22 mJy. For comparison, the previous detections with IRAM/MAMBO-2 needed four times longer on-source time for a noise level of $\sim$ 0.7 mJy (Scholz et al. 2006). Note that this was achieved with only the partially completed ALMA array (15 antennas). With the fully completed array, ALMA will fundamentally improve our knowledge. It will allow us to observe large samples in an efficient manner, push the sensitivity limits for disk masses to fractions of a Jupiter mass, study the gas component from the CO emission, and also provides the opportunity to resolve large numbers of brown dwarf disks. In combination with the completed surveys with Spitzer, WISE, and Herschel, the expected ALMA data will become a very powerful probe of the disk evolution in substellar objects.

3.4. Summary

Brown dwarfs harbour disks that are scaled down versions of T Tauri disks. All physical processes observed in circumstellar disks are also found in their circumsubstellar siblings. The global disk properties (mass and radius) seem to scale roughly with central object mass. Moreover, the timescales of the disk evolution are remarkably similar as well.

In terms of brown dwarf formation scenarios, this might be the expected outcome, if brown dwarfs originate from the same processes that also form stars. However, in terms of disk evolution models, the similarity of stellar and substellar disks is somewhat surprising. Multiple processes that affect the disk evolution are expected to be a strong function of the mass or luminosity of the central object or the mass of the disk. These processes, partly mentioned in this review, include photoevaporation, disk fragmentation, magneto-rotational-instability, and grain growth. Observations of brown dwarf disks can help to constrain all these aspects and may prove to be a crucial test case for our understanding of disk evolution.

Given the similarity of stellar and substellar disks, it is not too daring to state that brown dwarfs are indeed likely to form their own miniature planetary systems, which could be scaled down versions of the diverse exoplanetary systems discovered over the past decade. While giant planets will be very rare, a small population of Earth-sized planets could exist (Payne & Lodato 2007), in addition to smaller rocky planets and asteroid belts. The various issues for the habitability of these miniature planetary systems have been outlined by Barnes & Heller (2013). While making a planet in orbit around a brown dwarf might be possible, living on such a planet seems difficult.

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