1. Introduction

Throughout their evolution, low-mass stars lose angular momentum. A typical young star contains several orders of magnitude less angular momentum per mass unit than the molecular cloud core from which it has formed (Bodenheimer 1995). Another couple of orders of magnitude are lost on the main sequence. Through the RGB phase, the angular momentum disposal continues. The white dwarf at the end of the timeline incorporates even less specific angular momentum than the late main sequence star (although we do not quite know by how much, Kawaler 2004). Basically, angular momentum conservation is very rare in the evolution of low-mass stars.

The main agent in the rotational braking of a low-mass star is the stellar magnetic field. During the T Tauri phase, the magnetic interaction between star and disk effectively prevents the spin-up of the star that would otherwise be expected due to contraction and mass infall. For the first few million years of their existence, a significant fraction of low-mass stars rotate with approximately constant period (e.g., Rebull et al. 2004, Herbst & Mundt 2005, Davies et al. 2014). The exact physical mechanism that allows them to do that is not quite clear, but is likely to be a combination of magnetic locking of star and disk as well as powerful winds (see Matt et al. 2010, 2012). Magnetically driven stellar winds control the rotation for the remainder of the pre-main sequence and the entire main sequence phase. On the main sequence, stellar angular momentum as well as indicators related to magnetic activity drop approximately with the square root of the age, a relation known for more than 40 years (Skumanich 1972).

Stellar rotation is interesting because it is deeply linked to many important physical aspects of stellar evolution – magnetic field generation, interior structure, disk evolution, winds, internal mixing, chemical evolution, as well as magnetic activity which has implications for habitability of planets. Also, the rotation period, measured from the periodic photometric modulation due to surface features, is one of the very few fundamental stellar parameters that can be derived for large numbers of stars with percent or better accuracy, completely independent of models. This makes it very tempting to use rotation as a secondary indicator to infer other parameters, for example, to estimate stellar ages, an area of research that has been coined gyrochronology (Barnes 2003).

Because of the propensity of low-mass stars to shed angular momentum, it is always interesting to study objects that buck the trend and manage to conserve or almost conserve angular momentum for significant periods of time. These objects give us information about the mass dependencies of the fundamental processes mentioned above, specifically, they tell us in which parameter regimes these processes fail. Planets are in this category, as are brown dwarfs, objects unable to sustain stable Hydrogen fusion and to attain thermodynamical equilibrium, with masses below 0.08 $M_\odot$. In this article I will give a summary of this exciting topic within the venerable research field of stellar rotation. I will mostly discuss the rotational evolution of young brown dwarfs (since this is the Star Formation Newsletter) and only briefly touch on the (equally exciting) topic of the rotation of evolved field brown dwarfs and the link to cloudy atmospheres (see Radigan et al. 2014, Metchev et al. 2015 and references therein).

For more details on everything that is cursorily summarised here, I refer the reader to the reviews in Protostars & Planets V by Herbst et al. (2007) and in Protostars & Planets VI by Bouvier et al. (2013). The former is heavily focused on observations and limited to the pre-main sequence stage, while the latter also includes a thorough overview of the theory side as well as the main-sequence evolution.

2. Observational timeline

The exploration of the rotation of very low mass stars and brown dwarfs lagged only a few years behind the discovery of these objects. In the mid and late 90s, several groups reported solid evidence that objects at the bottom of the main sequence and beyond are fast rotators (e.g., Basri & Marcy 1995, Martin 1998, Terndrup et al. 1999, Bailer-Jones & Mundt 1999). The first slowly rotating brown dwarfs with periods of several days were published by Jorgens et al. (2003) and Scholz & Eisloffel (2004, 2005) for objects in young clusters and star forming regions.

Rotation periods in young clusters are the low hanging fruit in this field. The dense populations of these regions allow for very efficient, multiplexed, deep, high-cadence
monitoring, using wide-field imagers at medium-sized telescopes. In addition, young brown dwarfs are late M dwarfs which exhibit significant magnetic spot activity, facilitating the measurement of rotation periods. Today we know periods for dozens substellar objects with ages of 1-5 Myr (see Fig. [1]), primarily thanks to a number of PhD projects devoted to studying the variability of young stars and brown dwarfs. This includes my own PhD work published in Scholz & Eisloffel (2004a, b, 2005, 2009, 2011), but also the work by Markus Lamm (Lamm et al. 2004, 2005), Maria Victoria Rodriguez-Ledesma (Rodriguez Ledesma et al. 2009, 2010) as well as Ann Marie Cody (Cody & Hillenbrand 2010, 2011, 2014). Some further periods for young brown dwarfs have been published by Baile-Jones & Mundt (2001), Zapatero Osorio et al. (2004), Caballero et al. (2004), and Scholz et al. (2012).

Earlier this year, we have used high-precision lightcurves from the revamped Kepler mission K2 to measure rotation periods for 16 young objects with masses close to or below the Hydrogen burning limit (Scholz et al. 2015, see Fig. [1]). These are members of the Upper Scorpius star forming regions, with ages between 5 and 10 Myr, a previously unexplored age regime for brown dwarf rotation. Recently Bieller et al. (2015) constrained for the first time the rotation period of a young brown dwarf with a mass below the Deuterium burning limit (lower limit of 5h). In all young regions studied so far, the brown dwarf period range from a few hours up to several days. Note that some of the published periods at ages of 1-5Myr are in the range of the breakup limit. If confirmed, this would have severe implications for the further evolution of these brown dwarfs (see Scholz & Eisloffel 2005).

Measuring periods for field brown dwarfs is more difficult, because they have to be monitored one by one. Also, the origin of periodic variability is different in the older, and therefore much cooler, field brown dwarfs. Their variability is most likely caused by inhomogeneous cloud coverage (‘weather’), instead of magnetic spots. While a few individual periods have been published earlier, the discovery of highly variable brown dwarfs at the L/T transition by Artigau et al. (2009) and Radigan et al. (2012) increased the interest in brown dwarf variability and motivated a number of monitoring projects for field brown dwarfs aimed at studying cloud properties, which resulted, almost as a side-product, in many known rotation periods (e.g., Radigan et al. 2014, Metchev et al. 2015). So far, the overwhelming majority of the published periods for field brown dwarfs are short – less than 20 hours – but there are some exceptions (see Metchev et al. 2015). Since the monitoring runs for most objects have also been short, the upper limit for brown dwarf periods remains poorly defined.

This overview is focused on photometrically measured rotation periods. In comparison with spectroscopic rotatio-

![Figure 1: Rotation periods for young brown dwarfs as a function of age, compared with evolutionary tracks assuming angular momentum conservation (solid red lines). The breakup period is plotted as well (dashed pink line). The green squares mark the median period for each sample; the green triangles the 10% and 90% percentile. The periods at 1 Myr (ONC) are randomly spread out in age for clarity. Data from Scholz & Eisloffel (2004, 2005), Rodriguez-Ledesma et al. (2009), Cody & Hillenbrand (2010), Scholz et al. 2015; for more details see Scholz et al. (2015).](image)
ity amplitude as indicator for accretion and, hence, disk, and find that the slow rotators all are accretors, which would be evidence for disk braking, but in a small sample which also included very low mass stars. Rodriguez Ledesma et al. (2010) find no connection between slow rotation and presence of the disk in their sample of ONC brown dwarfs, but they use near-infrared photometry as disk indicators. At near-infrared wavelengths, the photospheric emission of brown dwarf peaks and the disk is faint, which makes it very difficult to robustly detect the disk. Cody & Hillenbrand (2010) test the disk-rotation relation in the substellar regime for the first time with mid-infrared photometry and do not see evidence for a direct connection between rotation rate and the presence of a disk – but their sample only contains few brown dwarfs.

In our most recent study, we use the periods derived for brown dwarfs in Upper Scorpius in combination with literature data to trace for the first time the substellar rotational evolution from 1 to 10 Myr (Scholz et al. 2015). The ‘money plot’ from this paper is reproduced in Fig. 1 which simply shows periods vs. age in comparison with tracks assuming angular momentum conservation. We find that the period evolution over this age span is consistent with no angular momentum loss, i.e. no rotational braking at all. If disk braking occurs, the locking timescale is at most 2-3 Myr, significantly shorter than for low-mass stars. This finding is robust within the uncertainties for the cluster ages. However, we also identify the disk-bearing objects in our sample, using WISE photometry, and find that all objects in our sample which still harbour disks are among the slowest rotators. Thus, while disk braking seems to be very inefficient in brown dwarfs, as already found by Cody & Hillenbrand (2010) (and by Lamm et al. 2005 for slightly more massive objects), it does seem to be at work at least in a few selected objects which manage to retain their disks longest.

Since disk lifetimes in brown dwarfs are not vastly different from stars (see Dawson et al. 2013), these findings indicate that the interaction between star and disk changes as we go to very low masses. Low ionisation at the inner disk edge (due to lower luminosity), lower mass accretion rates, as well as changes in the magnetic configuration all seem plausible explanations at this stage, but this needs to be explored in detail. In any case, whatever braking mechanism is at work in low-mass T Tauri stars, it should become inefficient in the substellar regime.

4. Also: inefficient wind braking

Wind braking controls the long-term rotational evolution of solar-mass stars. By the time stars with spectral type F to K have reached the age of the Hyades (600 Myr), they have settled onto a well defined period-mass relationship, a kind of ‘main sequence’ of rotational evolution. At this point the rotation period of low-mass stars is a function of mass and age, and little else (at least once binary stars in tidal interaction have been eliminated). With decreasing mass, the time objects need to converge to the rotational main sequence increases substantially (Irwin et al. 2011, Scholz et al. 2012, Newton et al. 2015): at 0.1-0.3 $M_{\odot}$, the spindown timescale is in the range of gigayears. The origin of this mass dependence is not well understood, but is likely related to the details of the wind physics and/or magnetic field generation.

The fast rotation of most field brown dwarfs indicates that this trend continues in the brown dwarf regime. Extrapolating from the evolutionary tracks for very low mass stars, we would expect brown dwarfs to retain their fast rotation rates for more than 5 Gyr. In addition to changes in magnetic field properties, most of the atmospheres of brown dwarfs eventually become too cool for an efficient coupling between plasma and magnetic field (Mohanty et al. 2003, Rodriguez-Barrera et al. 2015), which mostly shuts down persistent Hα and X-ray activity (apart from transient events) and may further impede rotational braking. Based on the currently known periods, however, there is evidence for some rotational braking on long timescales, but the angular momentum loss rate may be ∼10000 times weaker than in solar-mass stars (Bouvier et al. 2013). Large and unbiased period samples of field brown dwarfs at various ages are needed to constrain this further. At this stage, however, it seems clear that wind braking in brown dwarfs does not work very well.

5. A universal spin-mass relation?

In terms of their rotational evolution, brown dwarfs are much more like giant planets than stars – they retain their initial rotation rates for cosmological timescales. Therefore, it makes sense to compare rotation rates of brown dwarfs with those of planets. Solar system planets which are not tidally spun down, e.g. Mars, Jupiter, Saturn, Uranus, Neptune, obey a surprisingly strict relation between equatorial rotational velocity and mass (e.g., Hughes 2003), shown in Fig. 2. The Earth falls slightly below this correlation due to tidal interaction with the Moon, but fits the line fairly well when the Moon ‘is put back into Earth’ (Hughes 2003). This impressive relation can also be extended towards lower masses by including asteroidal data. As shown by Snellen et al. (2014), the rotational velocity for the young, massive exoplanet $\beta$ Pic b also falls on this spin-mass relation, at least given the errors on its mass. Note that a similar trend is also apparent when plotting angular momentum or specific angular momentum instead of rotational velocity. The relation is likely to be directly linked to the formation processes, presumably to the growth of planets in the protoplanetary disk.

In Fig. 2 I overplot the typical range of rotational velocities, inferred from periods, for field brown dwarfs (black line, based on a period range from 2 to 20h, see Metchev
then conceivable that the few brown dwarfs that obey the spin-mass relation might be the exceptions that form like giant planets and are ejected at an early evolutionary stage from the disk. If this relation really holds for all young substellar objects formed in disks, a hypothesis we need to test further, this could help us to distinguish brown dwarf formation scenarios.

On the other hand, brown dwarfs do spin down, albeit slowly, which makes the interpretation of Fig. 2 more difficult. Planets not affected by tidal interactions might be the only objects in the Galaxy that retain their primordial rotation rate and conserve angular momentum. By including brown dwarfs in the spin-mass diagram, we see the subtle emergence of the mechanisms that are responsible for the efficient spindown of stars.

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Figure 2: Equatorial rotational velocity (in km/s) vs. mass (in Jupiter masses) for brown dwarfs in comparison with solar system planets (excluding Venus and Mercury) and β Pic b. For brown dwarfs we show the typical range of rotational velocities. Unpublished figure, adapted from Snellen et al. (2014). The dashed line is not a fit, but only overplotted to illustrate the planetary spin-mass relation.