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Rotation and disk accretion in very low mass stars and brown dwarfs

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Abstract. The regulation of angular momentum is one of the key processes for our understanding of stellar evolution. In contrast to solar-mass stars, very low mass (VLM) objects and brown dwarfs are believed to be fully convective. This may lead to major differences of rotation and activity, since fully convective objects may not host a solar-type dynamo. Here, we report on our observational efforts to understand the rotational evolution of VLM objects.

Key words. Stars: activity, evolution, formation, low-mass, brown dwarfs, late-type, rotation

1. Introduction

Rotation is one of the key parameters for stellar evolution. It is the parameter that – at least in some well-behaved objects – can be measured to the highest accuracy. A precision for the rotation periods of 1 : 10000 is possible.

In solar mass stars the investigation of their rotation has allowed us new insights into their evolution (Bodenheimer 1995, Bouvier et al. 1997, Stassun & Terndrup 2003). It has become clear that angular momentum regulation is a direct consequence of basic stellar physics: most of the angular momentum of a fragmenting and collapsing molecular cloud is lost in the course of the formation of protostars. The specific angular momentum of protostars is, however, still one or two orders of magnitude higher than that of young main sequence stars. On the other hand, in their T Tauri phase solar-mass stars rotate slowly although they are accreting. The magnetic coupling between the star and its disk, and consequent angular momentum removal in a highly collimated bipolar jet are thought to be responsible for this rotational braking (Camenzind 1990, Königl 1991, Shu et al. 1994). After the dispersal of the disk, and thus loss of the braking mechanism, the rotation is observed to accelerate as the stars contract towards the zero-age main sequence. On the main sequence the rotation rates of solar-mass stars decrease again because of angular momentum loss through stellar winds.

Rotation can be investigated either by measuring stellar photospheric lines spectroscopically, or by the determination of rotation periods from photometric time series observations. While the former suffers from projection effects – the unknown inclination angle of the rotation axis with respect to the line of sight – the latter can be determined with high precision and independent of inclination angle. For our monitoring programme we therefore decided to follow the photometric time series approach to obtain precise rotation periods.

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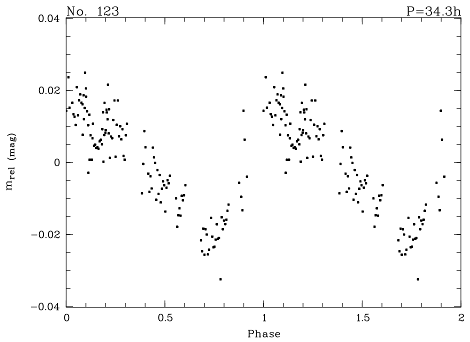

Fig. 1. Phase-folded light curve for a 50 M_{jup} brown dwarf in the epsilon Ori field. The measured rotation period is 34.3 h, and the light curve comprises of 129 measured data points.

2. Observations and data analysis

Since hardly any rotation periods for VLM objects and brown dwarfs with ages older than 3 Myr were known, it was necessary to create a database complementing the known rotation periods of solar-mass stars.

In the course of our ongoing monitoring programme we have so far obtained rotation periods for 23 VLM objects in the cluster around sigma Ori (Scholz & Eislöffel 2004a), for 30 in the field around epsilon Ori (Scholz & Eislöffel 2004c), which are belonging to the Ori OBIb association, and for 9 objects in the Pleiades open cluster (Scholz & Eislöffel 2004b). With ages of about 3, 5, and 125 Myr these three groups of VLM objects form an age sequence that already allows us insights into a relevant part of their young evolution.

Our time series photometry was done with the Wide Field Imager (WFI) at the ESO/MPG 2.2-m telescope on La Silla in epsilon Ori, and with the CCD camera at the 1.23-m telescope at the German-Spanish Astronomy Centre on Calar Alto (CA) in the Pleiades. The sigma Ori cluster was observed in two campaigns with the CCD cameras at the 2-m Schmidt telescope in Tautenburg (TLS) and at the 1.23-m telescope on Calar Alto. Our data analysis is described in full detail in Scholz & Eislöffel (2004a) and Scholz & Eislöffel (2004b). Fig. 1 shows an example for a final phase-folded light curve of a brown dwarf in the epsilon Ori field.

3. Rotation and variability of VLM objects

The general interpretation for the observed periodic variability in the light curves of our VLM targets are surface features, which are asymmetrically distributed on the surface and are co-rotating with the objects. Such surface features could arise either from dust condensations in the form of "clouds", or from magnetic activity in the form of cool "spots". Since all our objects, because of their youth, have surface temperatures $T_{\rm eff} > 2700$ K (Baraffe et al. 1998) corresponding to spectral types earlier than M8, and thus higher than the dust condensation limits, we are most likely observing the effects of cool, magnetically induced spots.

It is interesting to compare the photometric amplitudes of the periodic variations in the light curves with those of more massive cluster members. Such a comparison can be done for the Pleiades, for which the required photometric information for solar-mass stars is available from the Open Cluster Database (provided by C.F. Prosser (deceased) and J.R. Stauffer). Fig. 2 shows that larger amplitude variations are only observed in the higher mass objects. It is statistically significant that the amplitude distributions for higher and lower mass objects are different. That only amplitudes smaller than 0.04 mag are observed in the VLM objects may be attributed to the fact that a) the relative spot covered areas of their surfaces are smaller, b) their spot distributions are more symmetric or c) the spots have a lower relative temperature contrast with the average photosphere.

Investigating the mass dependence of the rotation periods for the VLM and solar-mass objects in the Pleiades, we find that their period distributions are also different. Fig. 3 shows that among the VLM objects we are lacking members with rotation periods of more than about two days, while the solar-mass objects show periods of up to ten days. Although our photometric monitoring covered a time span of 18 days, we might have missed slow rotators

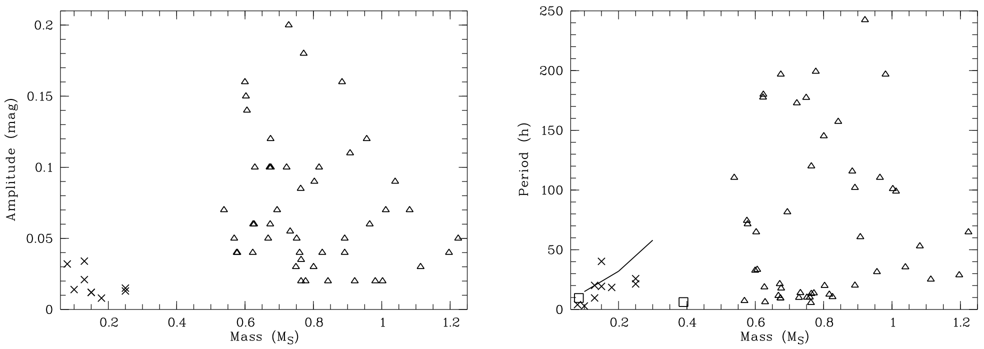

Fig. 2. Photometric amplitude versus mass for Pleiades stars from the Open Cluster Database (triangles, see Sect. 3 for complete references) and our targets (crosses). The detection limit for the solar-mass stars is 0.02 mag, explaining the lack of stars with very low amplitudes in this sample.
Rotation periods versus mass in the Pleiades. Our rotation periods for VLM objects are shown as crosses. Triangles mark the periods for solar-mass stars from the Open Cluster Database. The two squares show periods from Terndrup et al. (1999) The solid line marks the upper limit to the observed $v \sin i$ values of Terndrup et al. (2000).

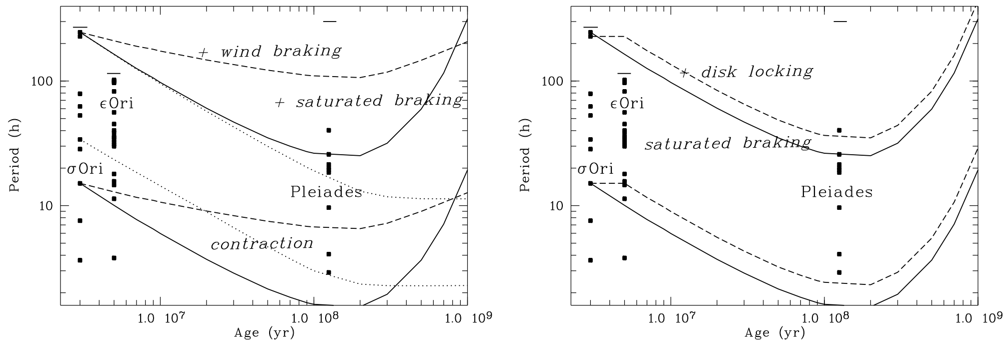

Fig. 3. Rotational evolution of VLM objects. The evolution of the rotation periods for a couple of objects for a model with hydrostatic contraction only is shown as dotted lines. The model with additional Skumanich type wind braking is shown as dashed lines, while saturated wind braking models are shown as solid lines.
Rotational evolution of VLM objects. The evolution of the rotation periods for a couple of objects for a model with hydrostatic contraction and saturated wind braking are shown as solid lines, as in Fig. 4, while a model with added disk-locking up to an age of 5 Myr is shown as dashed lines.

among the VLM objects, if their spot patterns evolved on a much shorter time scale, or if they did not show any significant spots. In order to investigate these possibilities, we converted the spectroscopically derived lower limits for rotational velocities from Terndrup et al. (1999) and references therein into upper limits for the rotation periods of the VLM objects using the radii from the models by Chabrier & Baraffe (1997). These rotational velocities should not be affected by the evolution of spot patterns on the objects. The derived upper period limits are shown in Fig. 3 as a solid line. With a single exception, all our data points fall below this line, and are thus in good agreement with the spectroscopic rotation velocities. Both complementary data sets indicate the absence of slow rotators among the VLM objects. In fact, our data show a trend towards faster rotation even in the VLM regime going to lower masses. A similar trend is also seen in our epsilon Ori sample, as well as in the Orion Nebula Cluster data by Herbst et al. (2001).

4. Rotational evolution of VLM objects

We can now combine the periods for all three clusters, sigma Ori, epsilon Ori, and the Pleiades to try to reproduce their period distributions with simple models. These models should include essential physics of star formation and evolution as described in Sect. 1. Given the currently available amount of information, we project the period distribution for sigma Ori forward in time and comapre the model predictions with our observations for epsilon Ori and the Pleiades.

As a first step, we take into account only the hydrostatic contraction of the newly formed VLM objects. In this case the rotation periods evolve from the initial rotation period at the age of sigma Ori strictly following the evolution of the radii (dotted lines in Fig. 3). These radii were taken from the models by Chabrier & Baraffe (1997). It is evident that this model is in conflict with the observed Pleiades rotation periods. Half of the sigma Ori objects would get accelerated to rotation periods below the fastest ones found in the Pleiades of about 3 h. At the same time, even the slowest rotators in sigma Ori would get spun up to velocities much faster than the slower rotators in the Pleiades. Since the sigma Ori VLM objects surely will undergo a significant contraction process, it is evident that significant rotational braking must be at work until they reach the age of the Pleiades.

Therefore, in a second model we add a Skumanich type braking through stellar winds (Skumanich 1972). This wind braking acts to increase the rotation periods $\sim t^{1/2}$, see the dashed lines in Fig. 3. According to this model, some of the sigma Ori slow rotators now get braked so strongly that they would become clearly slower rotators than are observed in the Pleiades (see also Sect. 3). This indicates that even the slowest sigma Ori rotators seem to rotate so fast, that they are beyond the saturation limit of stellar winds (Chaboyer et al. 1995, Terndrup et al. 2000, Barnes 2003). In this saturated regime, angular momentum loss is assumed to depend only linearly on angular rotational velocity, thus rotation periods increase exponentially with time. The solid lines in Fig. 3 follow our model which includes contraction and saturated wind braking. The period evolution of this model clearly is the most consistent with our data.

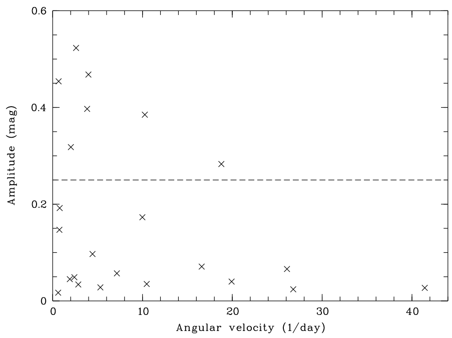

Fig. 4. Angular velocity versus amplitude. The dashed line delineates the separation between low-amplitude and high-amplitude objects.

For a few of our objects in sigma Ori we found evidence that they may possess an accretion disk (see below). Therefore, it is interesting to explore, if disk-locking at young age may play a role for the evolution of rotation periods. Assuming disk-locking for an age up to 5 Myr, typical for the occurrence of accretion disks in solar-mass stars, rotation periods would remain constant from the age of sigma Ori (3 Myr) to the age of 5 Myr. This disk-locking scenario was combined with the saturated wind braking, with an adapted spindown time scale. It is shown in Fig. 3 as dashed lines for two objects, together with the pure saturated wind braking model discussed above (solid lines). The period evolution for both models is very similar. Thus from our currently available rotation periods for these three clusters alone, there is no strong evidence for disk-locking on VLM objects.

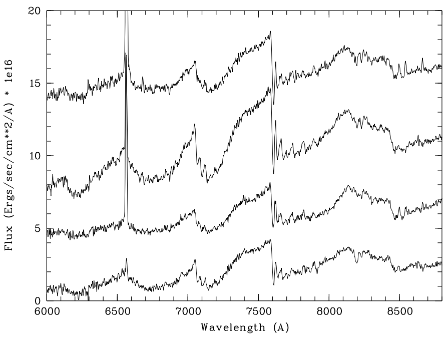

Fig. 5. Optical spectra for three highly variable targets (top three) and one non-variable target in sigma Ori.

5. Accretion, time variability, and disks in sigma Ori

We note that a few of the VLM objects in the two Orion regions also show large amplitudes of up to 0.6 mag (see Fig. 4). These variations are, however, of a more irregular character and most likely result from hot spots originating from accretion of circumstellar disk matter onto the object surface (see also Fernández & Eiroa 1996). Optical spectra of some of these objects in sigma Ori show indeed emission lines in Hα, the far-red Calcium triplet, and – in some cases – even forbidden emission lines of [OI]$\lambda\lambda$6300,6363 and [SII]]$\lambda\lambda$6716,6731, which are typical of accretion (see Fig. 5).

It is therefore interesting to see if near-infrared excess emission, an indicator for accretion disks, can be detected in the high-amplitude variables. Fig. 6 shows that non-variable and low-amplitude periodic variables in our σ Ori field scatter around the isochrone for 3 Myr taken from Baraffe et al. (1998), as expected for diskless objects in this cluster with negligible interstellar reddening. The high-amplitude variables, on the other hand, mostly lie in the reddening path or even redward of it. These objects thus must suffer from intrinsic reddening, indicating that they indeed possess disks. With their photometric variability, spectral accretion signatures, and indications for near-infrared excess emission from disks appear to be the low-mass and substellar counterparts to solar-mass T Tauri stars.

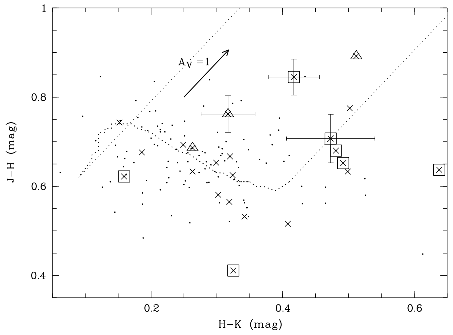

Fig. 6. (H-K,J-K) colour-colour diagram for sigma Ori. Crosses are periodically variable objects. Overplotted symbols flag objects with high photometric amplitude. Squares: light curve amplitude exceeds 0.25 mag, and thus mark high-amplitude variables, triangles are transition objects with amplitudes between 0.1 and 0.25 mag. The solid line indicates the 3 Myr isochrone from the Baraffe et al. models. Dotted lines show the interstellar extinction vector calculated from Mathis (1990). A reddening vector for $A_V = 1$ mag is given.

6. Conclusions

We report results from our photometric monitoring of VLM objects in the clusters around sigma Ori, epsilon Ori, and the Pleiades, and first attempts to model their rotational evolution.

VLM objects show shorter rotation periods with decreasing mass, which is observed already at the youngest ages, and hence must have its origin in the earliest phases of their evolution.

Combining the rotation periods for all our objects, we find that their evolution does not follow hydrostatic contraction alone, but some kind of braking mechanism, e.g. wind braking similar to the one observed in solar-mass stars, is required as well. Such a wind braking is intimately connected to stellar activity and magnetic dynamo action (Schatzman 1962). On the other hand, all the investigated VLM objects are thought to be fully convective, and therefore may not be able to sustain a solar-type large-scale dynamo, which is at the heart of the Skumanich type angular momentum loss of solar-mass stars. In fact, our modeling shows that such a Skumanich type wind braking cannot explain our data, while saturated angular momentum loss following an exponential braking law can. This, and the observed small photometric amplitudes may advocate a small-scale magnetic field configuration, and may support turbulent dynamo scenarios.

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