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Rotational evolution of low mass stars: The case of NGC 2264⋆

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Abstract. Our study is based on an extensive photometric monitoring program in the young (2–4 Myr) open cluster NGC 2264 by Lamm et al. (2004a). This program resulted in a sample of 405 periodic variables which are most likely pre-main sequence (PMS) members of the cluster. The periodic variability of these stars results from the rotational modulation of the light by stellar spots. In this paper we investigate the rotation period evolution of young stars. This is done by comparing the period distribution of the older NGC 2264 with that of the younger Orion Nebular Cluster (ONC, age: ∼1 Myr) which is known from the literature. The age ratio between the two clusters was estimated on the basis of PMS models to be about $2^{+0.75}_{-0.5}$. We find that the period distribution of NGC 2264 is similar in form to the ONC but shifted to shorter periods. In both clusters the period distribution depends strongly on the mass and it is bimodal for higher mass stars with $M \gtrsim 0.25\ M_\odot$ while it is unimodal for lower mass stars with $M \lesssim 0.25\ M_\odot$. In addition the lower mass stars rotate much faster on average than the higher mass stars. Quantitative comparison between the period distributions of both clusters suggests that a large fraction (about 80%) of stars have spun up from the age of the ONC to the age of NGC 2264. Based on this estimate and the estimated age ratio between the two clusters we find that the average spin up by a factor of 1.5−1.8 from the age of the ONC to the age of NGC 2264 is consistent with a decreasing stellar radius and conservation of angular momentum, for most stars. However, within NGC 2264 we did not find any significant spin up from the younger to older stars in the cluster. We also found indications for some ongoing disk-locking in NGC 2264, in particular for the higher mass stars. Our analysis of the period distribution suggests that about 30% of the higher mass stars in NGC 2264 could be magnetically locked into co-rotation with their inner disk. In the case of the lower mass stars, disk-locking seems to be less important for the rotational evolution of the stars. This interpretation is supported by the analysis of the stars' Hα emission. This analysis indicates that the locking period of the higher mass stars is about $P = 8$ days. For the lower mass stars this analysis indicates a locking period of about 2–3 days. We argue that the latter stars are probably not "completely" locked to their disk and propose an evolution scenario for these stars which we call "moderate angular momentum loss". In this scenario angular momentum is continuously removed from the stars but at a rate too low to lock the stars with a constant rotation period. We have done a detailed comparison with the recently published rotational period study of NGC 2264 of Makidon et al. (2004). Even though their obtained period distribution of their quality 1 data on NGC 2264 is indistinguishable within the statistical errors from ours, we come to quite different conclusions about the interpretation. One major reason for these discrepancies is probably the large inhomogeneity of the "whole" Orion region with which Makidon et al. (2004) compare their NGC 2264 data, while we compare our NGC 2264 data only with the ONC, which is the youngest and most homogeneous cluster of the Orions OBI association.

Key words. Galaxy: open clusters and associations: individual: NGC 2264 – Galaxy: open clusters and associations: individual: ONC – stars: pre-main sequence – stars: rotation – stars: formation

1. Introduction

An important open question in the theory of star formation is the evolution of angular momentum. It has been recognised for many decades that the specific angular momenta of interstellar clouds are many orders of magnitude higher than that of the Sun and other main sequence (MS) or pre-main sequence (PMS) stars. In the literature this discrepancy is often called the angular momentum problem which was first well expressed by Spitzer (1978). During the star formation process, angular momentum cannot be conserved since otherwise it would be impossible for a molecular cloud to be incorporated into a star. It is believed that during the different evolutionary steps of stellar formation, several different mechanisms remove angular momentum from the molecular cloud, the protostar, and later even from the visible T Tauri star (TTS). In this way the specific angular momentum is continuously reduced (for a review see Bodenheimer 1989).

Observationally, our best hope of constraining the angular momentum evolution of young visible stars is to obtain stellar rotation rates (and stellar radii) for objects at a variety of ages and masses. In the last two decades the determination of stellar rotation rates for both PMS and MS stars has made

⋆ Full Table 1 is only available in electronic form at the CDS via anonymous ftp to cdsarc.u-strasbg.fr (130.79.128.5) or via http://cdsweb.u-strasbg.fr/cgi-bin/qcat?J/A+A/430/1005 substantial progress and forms the basis of our current picture of the angular momentum evolution of solar-like stars.

The existence of rapidly rotating stars on the zero-age main sequence (ZAMS, e.g. Stauffer & Hartmann 1987), i.e., the spin up of stars from the PMS phase to the ZAMS, can simply be explained by gravitational contraction of the stars and only marginal loss of angular momentum. However, the existence of slow rotators and the broad period distribution of ZAMS stars in general can be only explained if during the TTS phase significant angular momentum loss is present and is in addition rather different from star to star. A magnetic interaction between stellar magnetospheres and circumstellar disks (disk-locking) has been proposed to cause the spin down of stars during the PMS evolution (Edwards et al. 1993). This means that classical (i.e. Skumanich-like) stellar winds alone are unable to explain this rotational evolution because of the large dispersion of rotational velocities among ZAMS stars (Krishnamurthi et al. 1997).

To date it is generally believed that magnetic star-disk interaction and the associated strong outflows control the angular momentum evolution of the stars during the PMS phase. This assumption is supported by the observational result that classical TTSs (CTTSs) with inner disks are rotating more slowly than weak-line TTSs (WTTSs) without inner disks (Edwards et al. 1993; Bouvier et al. 1993). Since the pioneering work of Ghosh & Lamb (1979a,b) and Camenzind (1990) several models for a disk-star interaction were developed (Königl 1991; Shu et al. 1994; Ostriker & Shu 1995).

The detailed mechanism for braking differs among the models. In the model of Shu et al. (1994) the star is *locked* into co-rotation with the inner disk which is truncated at some radius R_T. The rotation period of the star is equal to the Keplerian rotation period of the material in the disk at the "co-rotation radius" (R_C) which is slightly larger than R_T and is set by the balance of accretion ($\dot{M}$) and magnetic field strength $B_\star$ of the star. Angular momentum is transferred from the star to the disk via the torque of the magnetic field. The circumstellar disk itself and therefore the whole system (disk and star) loses angular momentum through a disk wind which is driven by (quasi) open magnetic field lines.

The disk-locking scenario is observationally supported by rotation period studies in the Orion Nebular Cluster (ONC, age $\approx$ 1 Myr) where Attridge & Herbst (1992) have first discovered a bimodal period distribution for higher mass stars ($M \geq 0.25\ M_\odot$, using the evolution tracks of D'Antona & Mazzitelli 1994) which was later confirmed by Herbst et al. (2001, 2002). In contrast, the period distribution of stars with lower masses was found to be unimodal. The bimodality of the higher mass stars is interpreted as an effect of disk-locking and the period distribution of Herbst et al. (2002) suggests that the locking period of higher mass stars in the ONC is about $P = 8$ days, while stars with shorter periods are presumably not locked to their disks. The locking period of 8 days is in agreement with the rotation periods measured for CTTSs in other stars forming regions (Bouvier et al. 1993).

Stassun et al. (1999) were not able to confirm the existence of a bimodal period distribution in the ONC. Furthermore, they did not find any differences between the rotation periods for WTTSs and CTTSs. Therefore, Stassun et al. (1999) suggested that a large spread in initial rotation periods may be much more important than the effect of disk-locking. However, their study is strongly biased towards periods with $P \leq 8$ days and towards lower mass stars which is probably the reason for their non-detection of a bimodal distribution. In addition Herbst et al. (2000) have shown the differences between the different studies are because Stassun et al. (1999) did not distinguish between low and high mass stars.

Rebull (2001) and Carpenter et al. (2001) also report large numbers of rotation periods in Orion and neither finds a bimodal distribution. The likely reason for that is that Orion is a heterogeneous association with many different aged populations present. To avoid the drawbacks of comparing our NGC 2264 sample with a heterogeneous sample we concentrate here on a comparison with the ONC (Ori OB Id) since it is the youngest and most homogeneous part of Orion. The importance of a homogeneous sample is further emphasised and discussed in our detailed comparison with the recently published rotational period study of NGC 2264 by Makidon et al. (2004; see Sect. 8).

Assuming that disk-locking can strongly influence the angular momentum evolution of young stars, several questions naturally arise from the results of the rotational studies in the ONC:

1. Is the period distribution similar in other young clusters, i.e. does environment play a role in setting up the initial period distribution?
2. How many PMS stars interact with their disks? Is disk-locking inefficient for lower mass stars and can their unimodal distribution observed in the ONC result from a lower fraction of locked stars?
3. How does the period distribution evolve with time and when do the stars typically decouple from their disks? Herbst et al. (2002) have estimated a star-disk interaction half-life of $\tau \approx 0.7$ Myr. On the other hand stellar evolution models apparently require disk-locking times of 3–10 Myr in order to reproduce the observed rotation period distribution of ZAMS stars (e.g. Krishnamurthi 1997).

To answer these questions it is necessary to measure rotation periods of large samples of PMS stars in clusters with different ages. On the PMS, photometric monitoring programs for the determination of rotation periods were mainly focused on the ONC where a multiplicity of rotation periods were measured (Attridge & Herbst 1992; Herbst et al. 2001, 2002; Rebull 2001; Stassun et al. 1999). In addition, a few rotation periods are available for stars in the Taurus Auriga Cloud (Bouvier et al. 1993), IC 348 (Herbst et al. 2000), and NGC 2264 (Kearns & Herbst 1998; Kearns et al. 1997). However, a statistically significant set of known periods exists only for the ONC. For a better understanding of the angular momentum evolution it is essential to know the rotation periods of many stars with a age different from that of the ONC stars.

Aside from the ONC, the open cluster NGC 2264 is perhaps the best target for a detailed rotational study of low-mass PMS stars, since it is sufficiently nearby (760 pc, Sung et al. 1997), fairly populous, and with an estimated age of 2–4 Myr

Table 1. Photometric data, period (P), the error of the period ($P_{\rm err}$), and spectral types of all 405 periodic variable PMS stars found in Paper I. The spectral types are taken from (1) Young (2000); and (2) Rebull et al. (2002a), Rebull (2002). We also list our internal ID for each star from which the used exposure time (5, 50 or 500 s) and the CCD-chip (a–h) is evident. The full table is available electronically at the CDS. For cross identification of the stars see Table 4 of Paper I.

Star	α(J2000)	δ(J2000)	$I_{\rm C}$	err	$V - I_{\rm C}$	err	$R_{\rm C} - I_{\rm C}$	err	$R_{\rm C}$ – Hα	err	P	$P_{\rm err}$	SpT	Internal ID
71	6:39:51.09	9:36:33.2	15.84	0.09	2.42	0.04	1.32	0.04	–3.08	0.02	1.36	0.05	M1:[2]	50 e 741
249	6:39:52.69	9:37:37.7	17.49	0.01	3.29	0.02	1.88	0.01	–2.97	0.03	2.14	0.13	.....	500 e 1673
731	6:39:56.87	9:31:35.2	17.76	0.01	3.15	0.02	1.86	0.01	–2.81	0.04	0.95	0.02	.....	500 e 1076
1025	6:39:59.84	9:33:41.9	14.90	0.01	1.67	0.01	0.83	0.01	–3.21	0.02	1.29	0.04	K7[2]	50 e 606
1146	6:40:00.92	9:32:08.6	16.57	0.01	2.91	0.01	1.72	0.01	–2.93	0.04	1.56	0.07	.....	500 e 1135
1177	6:40:01.19	9:42:36.9	15.84	0.01	2.35	0.01	1.32	0.01	–3.10	0.01	3.92	0.40	.....	50 d 136
1316	6:40:02.65	9:35:24.6	15.19	0.01	2.36	0.01	1.31	0.01	–2.78	0.03	4.55	0.54	.....	50 e 678
1473	6:40:04.02	9:27:07.5	14.53	0.01	1.91	0.01	0.97	0.01	–3.17	0.01	0.82	0.02	M0[2]	50 e 277
1490	6:40:04.19	9:47:06.1	17.77	0.01	3.18	0.02	1.88	0.01	–2.96	0.02	1.29	0.05	.....	500 d 739
1573	6:40:04.94	9:34:31.0	15.81	0.01	2.30	0.01	1.26	0.01	–3.04	0.02	6.30	1.03	.....	50 e 640
1704	6:40:06.00	9:49:43.2	14.86	0.01	2.21	0.03	1.22	0.02	–2.89	0.11	8.28	1.78	M2[2]	50 d 613
1748	6:40:06.35	9:39:34.0	13.66	0.01	1.55	0.01	0.79	0.01	–3.27	0.01	6.21	1.31	.....	50 d 12
1792	6:40:06.80	9:24:38.4	15.46	0.01	2.28	0.01	1.24	0.01	–3.06	0.02	7.22	1.35	M2.5[2]	50 e 116
1944	6:40:08.24	9:41:25.2	17.24	0.01	2.90	0.02	1.71	0.01	–2.96	0.03	1.66	0.08	.....	500 d 158
2024	6:40:08.86	9:34:10.6	15.53	0.01	2.45	0.01	1.37	0.01	–3.03	0.01	3.73	0.36	M3[2]	50 e 626
2205	6:40:10.87	9:40:07.7	15.92	0.01	2.42	0.01	1.35	0.01	–3.04	0.05	11.73	3.81	M3[2]	500 d 64
2227	6:40:11.07	9:45:26.8	17.91	0.01	3.10	0.02	1.84	0.01	–3.00	0.03	2.31	0.15	.....	500 d 542

(Park et al. 2000) it is about a factor of 2−4 older than the ONC. Therefore we selected the young open cluster NGC 2264 for an extensive photometric monitoring program which was described in a preceding paper (Lamm et al. 2004a, hereafter Paper I). In the study presented in Paper I we monitored about 10 600 stars in the NGC 2264 region over a very broad magnitude range ($9.8 \le I_{\rm C} \le 21$) corresponding to stars with masses from about 1.2 $M_\odot$ down into the substellar regime. This extensive monitoring program allowed us to identify about 600 new PMS stars in the cluster and in addition we could measure the rotation periods of 405 PMS stars.

In the paper presented here we discuss the derived period distributions for the lower and higher mass stars and the resulting conclusions for the disk-locking scenario. In the following section we briefly describe the observations. In Sect. 3 we calculate the age ratio between NGC 2264 and the ONC. In Sect. 4 we present and discuss the period distribution of NGC 2264, investigate its colour and mass dependence, and compare it with the period distribution of the ONC. In Sect. 5 we investigate whether there are indications for a different rotational behaviour of younger and older stars in NGC 2264. In Sect. 6 we investigate whether there are indications for ongoing disk-locking in NGC 2264. In Sect. 7 we summarise the possible rotational evolution scenarios from the ONC to NGC 2264. In Sect. 8 we present a detailed comparison between the NGC 2264 study of Makidon et al. (2004) and this paper and in Sect. 9 we summarise our major conclusions.

2. Observations

For details of the data acquisition, analysis and photometry we refer the reader to Paper I and we give here only a short summary. The results presented here are based on a photometric monitoring program of a $34' \times 33'$ field in NGC 2264 carried out with the Wide-Field-Imager (WFI) attached to the ESO/MPG 2.2 m telescope on La Silla, Chile. Observations were obtained on 44 nights in the $I_{\rm C}$ band during a period of two months between Dec. 2000 and Mar. 2001. Altogether we obtained typically 88 data points per object. The signal-to-noise ratio of each data point was $S/N = 30$ or better for stars fainter than $I_{\rm C} = 19.5$ mag. We also obtained several additional images through V, $R_{\rm C}$ and Hα filters. Relative and absolute photometry was obtained on 10 554 stars in the field with magnitudes extending to $I_{\rm C} \simeq 21$ mag.

All stars in the field have been checked for periodic brightness variations using two different periodogram techniques. First we used the *Scargle periodogram* described by Scargle (1982) and Horne & Baliunas (1986). Second we did the analysis using the *CLEAN periodogram* described by Roberts et al. (1987). For 543 of the 10 554 stars in the field we detected periodicity with a significance of 99% or better. Of these periodic variable stars we classified 405 stars as PMS members. The PMS nature of the stars was carefully deduced from their location in the $I_{\rm C}$ vs. $(R_{\rm C} - I_{\rm C})$ colour–magnitude-diagram and the $(R_{\rm C} - {\rm H}\alpha)$ vs. $(R_{\rm C} - I_{\rm C})$ colour–colour diagram. For a detailed discussion of the periodogram analysis and the selection of periodic PMS variables we refer again to Paper I.

The scientific discussion presented in this paper is only based on the sample of the 405 periodic variable PMS stars we found in Paper I for which we expect only a minor contamination with non-PMS stars. In Table 1 we summarise the basic properties of these periodic variables.

3. The age ratio of NGC 2264 and ONC

For a comparison of the rotation period distributions of the ONC and NGC 2264 it is essential to know the ages of the two clusters. However, the absolute ages depend strongly on

Table 2. Estimated mean ages of NGC 2264 ($t_{\mathrm{NGC\ 2264}}$) and the ONC (t_{ONC}) taken from the literature. Ages were taken from Hillenbrand (1997) for the ONC and from Park et al. (2000) for NGC 2264. Listed are the PMS evolution model employed in the study from which the cluster age was taken (SF94 = Swenson et al. 1994; DM97 = D'Antona & Mazzitelli 1994; BC98-I, II = Baraffe et al. 1998), the deduced cluster ages, and, if the same model was applied in both clusters, the resulting age ratio ($t_{\mathrm{NGC\ 2264}}/t_{\mathrm{ONC}}$).

Model	t_{ONC}	$t_{\mathrm{NGC\ 2264}}$	$\frac{t_{\mathrm{NGC\ 2264}}}{t_{\mathrm{ONC}}}$
SF94	1.5 Myr	2.1 Myr	1.4
DM94	0.5 Myr	0.9 Myr	1.8
BC98-I	...	4.3 Myr	...
BC98-I	...	2.7 Myr	...

the PMS evolution model used. In Sect. 4.3 we will show that for the investigation of the rotational evolution it is sufficient to know the mean age *ratio* between the two clusters which should be better constrained. Therefore, we first estimate the relative ages of NGC 2264 and the ONC in this section.

The ages of the two clusters used in the literature are 1 Myr for the ONC (Hillenbrand 1997) and 2–4 Myr for NGC 2264 (Park et al. 2000). These ages have been determined using several different PMS evolution models and are in some respects "*mean*" values of these different age estimates for each cluster. Using these numbers, the age ratio of the two clusters is between two and four. However, the deduced ages are very model dependent. Park et al. (2000) demonstrated for NGC 2264 that different models lead to cluster ages ranging from 0.9 Myr up to 4.3 Myr, i.e. the estimated cluster ages differ by a factor of 4.8. Therefore, the ages of the two clusters which are used in the literature are not consistent and it is necessary that the age ratio of the clusters is determined for each model separately. In this way the the resulting age ratios are less affected by differences of the adopted PMS models (e.g. the zero point).

For the age determination of the ONC, Hillenbrand (1997) used the two PMS evolution models by Swenson et al. (1994; hereafter SF94) and D'Antona & Mazzitelli (1994; hereafter DM94). These two PMS evolution models were also used for the age determination of NGC 2264 by Park et al. (2000). In addition Park et al. (2000) determined the age of NGC 2264 by employing two models of Baraffe et al. (1998; hereafter BC98-I and BC98-II). Table 2 summarises the results of the age determination of these studies in NGC 2264 and the ONC. For the models by SF94 and DM94, which were used in both studies, the resulting age ratios of the clusters are also listed. The estimated ages of the ONC vary by a factor of three while the determined ages of NGC 2264 vary by a factor of 4.8 (or 2.3 considering only the models SF94 and DM94).

In order to get another independent determination of the age ratio of NGC 2264 and ONC we determined the mean ages of the clusters by adopting an improved PMS evolution model of D'Antona & Mazzitelli (1997; hereafter DM97). For the age determination of NGC 2264 we used the sample of 589 variable PMS stars identified in Paper I (i.e. 405 periodic and 184 irregular variables). This is a much larger data set compared to the 208 cluster members used by Park et al. (2000) for the age

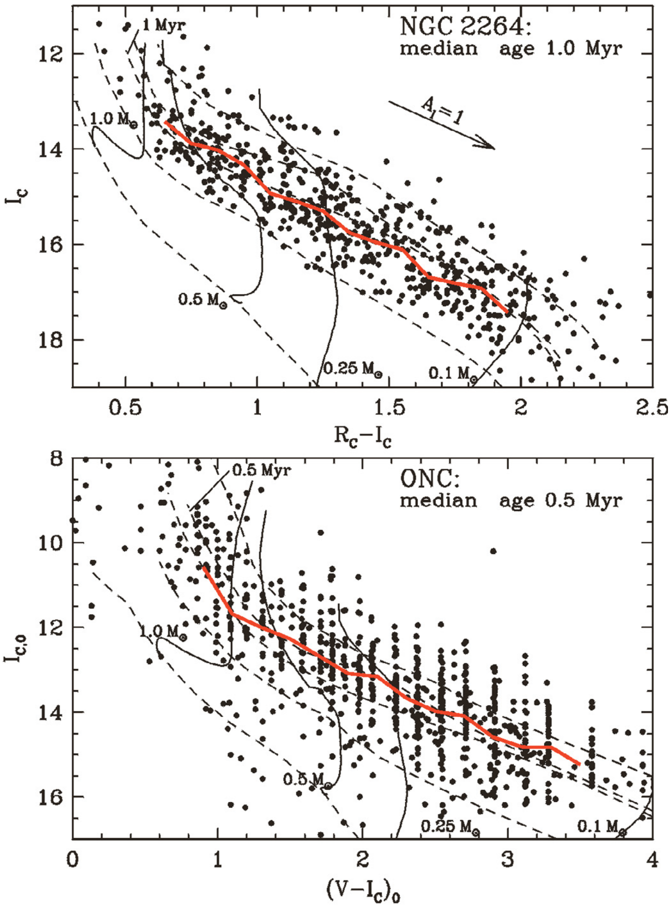

Fig. 1. *Top panel*: the colour–magnitude diagram of the 405 periodic and 184 irregular PMS variables in NGC 2264 found by Lamm et al. (2004a). The red dashed lines are (0.1, 0.5, 1.0, 5.0, and 200 Myr) isochrones and the blue thin solid lines are evolution tracks for four different masses (0.1, 0.25, 0.5, and 1.0 $M_{\odot}$) by D'Antona & Mazzitelli (1997). The isochrones and evolution tracks were reddened using the mean reddening $E(R_C - I_C) = 0.1$ and extinction $A_{I_C} = 0.25$ from Rebull et al. (2002a). The red thick solid line is the median I_C magnitude of the stars calculated in different colour bins. *Bottom panel*: the colour–magnitude diagram of 785 individually dereddened ONC stars with known spectral type taken from Hillenbrand (1997). The solid and dashed lines are (unreddened) evolution tracks and isochrones respectively for the same masses and ages as in the top panel.

determination of NGC 2264. In Fig. 1 we show the observed I_C vs. $(R_C - I_C)$ colour–magnitude diagram of these 589 stars in NGC 2264. Individual dereddening of all stars in this sample is not possible because reddening $E(R_C - I_C)$ and extinction A_{I_C} published by Rebull et al. (2002a) are available only for about 180 of these stars. Therefore we calculated reddened isochrones and evolution tracks of the DM97 model by using the mean values $E(R_C - I_C) = 0.10 \pm 0.02$ and $A_{I_C} = 0.25$ of the reddening and extinction towards NGC 2264 which were determined by Rebull et al. (2002a) adopting $R = E(B-V)/A_V = 3.1$. Alternatively it would have been possible to locate any reddened isochrones and evolution tracks of DM97 in an I versus $V - I$ colour magnitude diagram. Since we have no individual reddening of all stars available

Table 3. *Left*: the median I_C magnitude in $(R_C - I_C)$ colour bins of width 0.1 mag for stars in NGC 2264, where the listed $(R_C - I_C)$ colours are the colour of the bin centres. Also listed are the number of data points per bin which was used for the determination of the median magnitude, the logarithm of the median age, and the median age of the stars in each bin. The median ages were derived employing reddened PMS evolution models by D'Antona & Mazzitelli (1997) assuming mean values of $E(R_C - I_C) = 0.1$ and $A_{I_C} = 0.25$. *Right*: the same for ONC stars. Listed are the median $I_{C,0}$ magnitudes in $(V - I_C)_0$ colour bins of 0.2 mag width. The dereddened photometric data were taken from Hillenbrand (1997).

NGC 2264					ONC				
$(R_C - I_C)$	Median I_C	Data points	log (age/yr)	Age/Myr	$(V - I_C)$	Median I_C	Data points	log (age/yr)	Age/Myr
0.65	13.43	25	5.8703	0.7	0.90	10.58	49	5.9906	1.0
0.75	13.88	34	5.8720	0.7	1.10	11.68	50	6.0511	1.1
0.85	14.02	45	5.7753	0.6	1.30	12.00	34	5.7625	0.6
0.95	14.34	28	5.8484	0.7	1.50	12.27	53	5.6537	0.5
1.05	14.93	34	6.0931	1.2	1.70	12.68	76	5.6975	0.5
1.15	15.10	51	6.0614	1.2	1.90	13.09	60	5.7684	0.6
1.25	15.30	55	6.0374	1.1	2.10	13.16	41	5.6442	0.4
1.35	15.76	33	6.1667	1.5	2.30	13.67	100	5.7687	0.6
1.45	15.96	39	6.0933	1.2	2.50	13.98	76	5.7386	0.5
1.55	16.11	35	6.0285	1.1	2.70	14.09	63	5.3040	0.2
1.65	16.69	34	6.1856	1.5	2.90	14.59	63	5.6326	0.4
1.75	16.81	41	5.9817	1.0	3.10	14.82	54	5.5719	0.4
1.85	16.92	41	5.9279	0.8	3.30	14.83	43	5.2723	0.2
1.95	17.43	27	5.8179	0.7	3.50	15.24	23	5.3356	0.2
Mean age			5.9828	1.0 ± 0.3	Mean age			5.6566	0.5 ± 0.3

(and used therefore an average value), we preferred to do use $R - I$ colours, because they are less affected by reddening. Therefore any differences between individual and average reddening will have smaller effects on the location of individual stars with respect to the dereddened isochrones in the top part of Fig. 1.

For the determination of the mean age of NGC 2264 we first calculated the median I_C magnitude in $(R_C - I_C)$ colour bins of 0.1 mag width and determined the median age in each of these colour bins by applying the reddened isochrones of the DM97 model. The calculated median ages are listed in Table 3. The resulting mean age of NGC 2264 (i.e. the mean of the listed medians) is 1.0 ± 0.3 Myr (one sigma scatter).

The age of the ONC was calculated by using dereddened $I_{C,0}$ and V_0 photometry of 785 cluster members with known spectral type in the colour range 0.55 mag $\leq (V - I_C)_0 \leq$ 2.05 mag taken from Hillenbrand (1997). The $I_{C,0}$ vs. $(V - I_C)_0$ colour–colour diagram of the ONC is shown in the lower part of Fig. 1. In principle it would have been possible to proceed in the ONC in the same manner as in NGC 2264; i.e. using reddened isochrones instead of using individual reddening values for each star. Such a procedure probably would have produced spurious results, because the reddening towards the ONC is rather clumpy and much larger than in the case of NDC 2264. Fortunately there was no need for such a procedure, since individual reddening values are available from the literature.

Table 3 also lists the median ages of ONC stars calculated in 0.2 mag wide $(V - I_C)_0$ colour bins. The mean age of the ONC resulting from these medians is 0.5 ± 0.3 Myr. The median values of the newly calculated cluster ages for the two clusters yield an age ratio of $t_{\rm NGC\,2264}/t_{\rm ONC} \approx 2$. We note that the absolute ages of the clusters may be somewhat larger than is suggested by our analysis outlined above because the D'Antona & Mazzitelli (1997) models typically result in smaller ages compared with models by other authors. In addition the one-sigma scatter of the median ages (0.3 Myr) may also be smaller than the actual scatter in the ages (i.e. the scatter of the ages in each bin). Systematic errors on the ages could also be caused by imprecise relative distances of the two clusters.

However, taking our newly determined age ratio and the numbers listed in Table 2 into account we conclude that the age ratio of the two clusters ($t_{\rm NGC\,2264}/t_{\rm ONC}$) previously estimated as 2–4 is actually more likely in the range of 1.5–2.75 with a most probable value of about 2. Therefore we assume for the subsequent analysis that NGC 2264 is twice as old than the ONC.

4. The rotation period distribution: From the ONC to NGC 2264

4.1. The colour dependence of the rotation periods in NGC 2264

As a first step we investigate how the period distribution in NGC 2264 depends on the colour of the stars. We search for a colour dependence instead of a mass dependence of the rotation periods because masses are only known from the analysis of Rebull et al. (2002a) for about 150 of the 405 periodic variables. In addition the sample of stars with known masses is biased towards the higher mass regime.

Figure 2 shows both the period (P) and the angular velocity ($\omega = 2\pi/P$) as a function of the $(R_C - I_C)$ colour for all 405 periodic variable PMS stars. Also shown is the median of P and ω, respectively. Both medians were calculated in equally

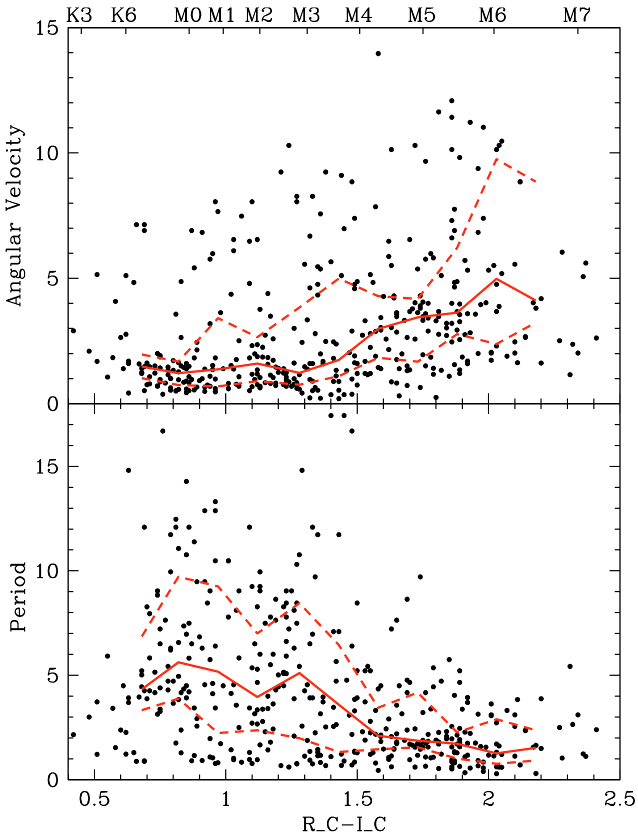

Fig. 2. *Top panel*: the angular velocity $\omega = 2\pi/P$ of the 405 periodic variables in NGC 2264 as a function of the observed $(R_C - I_C)$ colour. The solid line represents the median angular velocity calculated in fixed discrete colour bins of 0.15 mag width. The dashed lines represent the upper and lower quartiles in these bins. *Bottom panel*: the period P as a function of the $(R_C - I_C)$ colour for all periodic variables in NGC 2264. The solid and dashed lines are the median and the quartiles of the periods in colour bins of 0.15 mag width, respectively.

spaced colour bins of 0.15 mag width. It is evident that the range covered by the angular velocity or period is very large for a given colour. However, as indicated by the medians there is apparently a change in both the angular velocity and period distribution which occurs at $(R_C - I_C) \approx 1.3$ mag. Stars redder than this colour (i.e. lower mass stars) rotate on average much faster than the bluer stars (i.e. more massive stars).

In order to investigate the different rotational properties of lower and higher mass stars in more detail we have divided the sample of 405 periodic variables into two subsamples. The first subsample contains all stars with $(R_C - I_C) < 1.3$ mag while the second subsample contains redder stars with $(R_C - I_C) > 1.3$ mag. From Fig. 1 or Fig. 5 it is evident that this division corresponds approximately to a splitting the stars into two groups with $M > 0.25\ M_\odot$ and $M < 0.25\ M_\odot$ respectively. We note, however, that this is only an approximate mass estimate because reddening above or below average can shift higher mass stars into the redder or lower mass stars into the bluer regime.

4.2. The rotation period distribution of NGC 2264 and the ONC

For the further analysis we use the two subsamples of higher and lower mass stars in NGC 2264 defined in the previous section. The left panel of Fig. 3 shows the histograms of the period distribution for each of these two samples. It is evident that the period distributions of the two subsamples are significantly different. The most obvious difference is that higher mass stars with $(R_C - I_C) > 1.3$ mag show a bimodal period distribution while the period distribution of the lower mass stars with $(R_C - I_C) < 1.3$ mag is unimodal. In addition (and as already mentioned in the previous section) the lower mass stars rotate much faster on average than the higher mass stars. The median rotation periods of the higher and lower mass stars (indicated by the vertical doted lines in Fig. 3) are 4.7 days and 1.9 days, respectively; i.e., the lower mass stars rotate on average by a factor of 2.5 faster than the higher mass stars.

For comparison purposes the right panel of Fig. 3 also shows a reproduction of the period distribution of the ONC by Herbst et al. (2001, 2002). As in NGC 2264 the period distribution for the ONC depends on the stellar mass. The distribution is bimodal for the higher mass stars with $M > 0.25\ M_\odot$ and unimodal for lower mass stars with $M < 0.25\ M_\odot$. Since in NGC 2264 a colour of $(R_C - I_C) = 1.3$ mag corresponds roughly to a mass of $0.25\ M_\odot$ the period distributions in both clusters are unimodal for stars less massive than $0.25\ M_\odot$. The median rotation periods of the higher and lower mass stars in the ONC are 6.75 days and 3.3 days, respectively. Thus, the lower mass stars in the ONC rotate on average by a factor of two faster than the higher mass ONC stars which is the same trend as observed in NGC 2264.

Although the period distributions of the *higher mass stars* (top panels of Fig. 3) look very similar in both clusters, the locations of the peaks differ significantly. In NGC 2264 the peaks of the bimodal distribution are located at about $P = 1$ day and $P = 4$ days. In the ONC the corresponding peaks are shifted to longer periods and they are located approximately at $P = 1.5$ days and $P = 7.5$ days. Hence, the higher mass stars which build up the first peak in NGC 2264 at $P \approx 1$ day rotate by a factor of 1.5 faster than the higher mass stars located in the first peak of the ONC at $P \approx 1.5$ days. The ratio between the stars in the second peak of NGC 2264 and the ONC (at 4 days and 7.5 days, respectively) is 1.9.

For the *lower mass stars* the unimodal period distribution for NGC 2264 peaks at about $P = 1$ days while the peak in the distribution of the ONC is located at $P = 1.5$ days. Hence, the lower mass stars in NGC 2264 which build up the peak of the period distribution rotate by a factor of 1.5 faster than the stars which build up the peak in the period distribution of the ONC.

In summary, we find evidence for a spin-up of a significant fraction of the stars in NGC 2264 in comparison to the ONC, which is about a factor of two younger. This evidence is provided by the shorter median periods in NGC 2264 and the shift of the peaks to shorter periods in the distributions of NGC 2264 compared with the distributions of the ONC. The median periods of the distribution indicate that the higher and lower mass

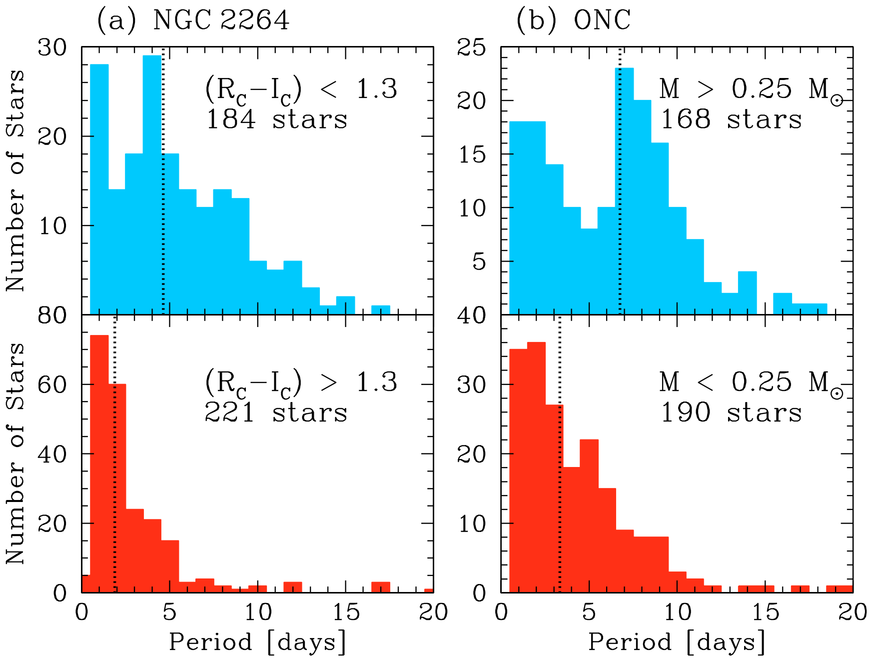

Fig. 3. a) *Left*: the period distribution for two different samples of periodic variable PMS stars in NGC 2264 (age: 2–4 Myr). The upper left histogram shows the period distribution for (higher mass) stars with $(R_C - I_C) < 1.3$ mag while the lower left histogram shows the period distribution for redder (lower mass) stars with $(R_C - I_C) > 1.3$ mag. This corresponds approximately to a division into stars with $M > 0.25\ M_\odot$ (top) and $M < 0.25\ M_\odot$ (*bottom*). **b)** *Right:* the period distribution of periodic variable stars in the ONC (age: 1 Myr) for two different *mass* regimes. The data are taken from Herbst et al. (2001, 2002).

stars in NGC 2264 are spun up relative to the corresponding ONC stars by a factor of 1.5 and 1.8, respectively. This is consistent with the spin up calculated from the shift of the peaks by a factor of 1.5–1.9. As we will show in the following section this amount of spin-up is consistent with stellar contraction based on PMS models and conservation of angular momentum. We note that not all stars in NGC 2264 spin up and it is likely that some stars maintain a longer rotation period; presumably these stars are still disk-locked (see below).

For NGC 2264 the ratio between the median periods of the higher and lower mass stars is 4.7/1.9 = 2.4. For the ONC this ratio is somewhat smaller, i.e. 6.75/3.3 = 2.0. This indicates that the lower mass stars in NGC 2264 spun up more than the higher mass stars or equivalently some higher mass stars in NGC 2264 spun up less or did not spin up at all. Since it is expected that some stars in NGC 2264 are still disk-locked (or at least have maintained a disk-lock between the age of the ONC and the NGC 2264 age) this can be explained by a larger fraction of disk-locked stars among the higher mass stars.

4.3. Spin-up with conserved angular momentum

In this section we examine whether for most stars their spin-up from the age of the ONC to the age of NGC 2264 described above is consistent with conservation of angular momentum. Here and in all following sections we assume that the ONC represents an earlier rotational evolution stage than NGC 2264; i.e. we assume that when NGC 2264 was at the age of the ONC the period distributions of NGC 2264 were identical to those of the ONC which we observe today.

For the following estimates we assume that the rotational evolution of the stars in both clusters can be described by:

1. full convection (polytropic structure); and
2. rigid rotation.

The first assumption is supported by detailed PMS models (e.g. of Krishnamurthi et al. 1997) which show that the total moment of inertia of TTSs with $M \leq 0.9\ M_\odot$ younger than 2 Myr is equal to the moment of inertia in the convective envelope of the stars. Nearly the same is true for stars younger than 4 Myr (and $M \leq 0.9\ M_\odot$), where a minimum of 97% of the total moment of inertia is in the convective envelope. The same result is achieved for stars less massive than 1.2 $M_\odot$ and younger than 2 Myr (see their Fig. 2). From the isochrones in Fig. 1 it is evident that almost all stars in our sample fulfil these conditions, i.e., their total angular momentum is almost completely in the convective envelope (we note that this condition is fulfilled for ≥99% of the stars in NGC 2264 if all are younger than 2 Myr and for ≥92% if all are younger than 4 Myr). We note that the assumption of full convection at all stages is equivalent to assuming a homologous structure.

It is well known that the luminosity of solar-like stars in the early PMS phase is generated almost entirely by gravitational contraction with nearly constant effective temperature (e.g. Hayashi 1966). According to the virial theorem one half of the released gravitational energy $E_{\rm grav}$ heats up the interior of the star while the other half is radiated, i.e.,

$$L = -\frac{1}{2}\frac{\mathrm{d}E_{\rm grav}}{\mathrm{d}t}. \qquad (1)$$

The assumed polytropic structure of the star yields the gravitational energy of (e.g. Kippenhahn & Weigert 1994):

$$E_{\rm grav} = -\frac{3}{5-n}\frac{GM^2}{R}, \tag{2}$$

where M and R are the stellar mass and radius, respectively, G is the gravitational constant, and n is the *polytropic index* which is defined by a pressure (P) density (ρ) relation of $P \propto \rho^{1+1/n}$ and is given by $n = \frac{3}{2}$ for a fully convective star. Since $L = 4\pi R^2\sigma T_{\rm eff}^4$ Eqs. (1) and (2) yield:

$$4\pi R^2\sigma T_{\rm eff}^4 = -\frac{1}{2}\frac{{\rm d}\left(\frac{3GM^2}{3.5R}\right)}{{\rm d}t}. \tag{3}$$

For constant mass M we obtain

$$\frac{{\rm d}R}{{\rm d}t} = -\frac{28\pi R^4\sigma T_{\rm eff}^4}{3GM^2}. \tag{4}$$

The integration of Eq. (4) (assuming M and $T_{\rm eff} \approx$ const.) yields

$$\frac{1}{R^3} - \frac{1}{R_0^3} = \frac{28\pi\sigma T_{\rm eff}^4}{GM^2}\,t, \tag{5}$$

where R_0 is the radius at the onset of star formation, i.e. at the birthline at $t = 0$. Since $R_0^3 \gg R^3$ for the PMS stars in both clusters one can neglect the second term on the left hand side of Eq. (5). If the effective temperature, $T_{\rm eff}$, is assumed to be constant (as supported by the isochrones in Fig. 1) we finally get $R \propto t^{-1/3}$.

We now calculate the evolution of the rotation period as a function of the stellar radius if angular momentum is conserved. The specific angular momentum of a star is given by

$$j = \frac{J}{M} = \frac{I\omega}{M}, \tag{6}$$

where J is the total angular momentum, I is the moment of inertia and $\omega = 2\pi/P$ the angular velocity of a star which rotates with period P. The moment of inertia can be written as $I = k^2R^2M$, where k is the radius of gyration which is $k = 0.45$ for a fully convective star (i.e., $n = 3/2$). We finally obtain for the specific angular momentum

$$j = \frac{2\pi k^2R^2}{P}. \tag{7}$$

Therefore, if the angular momentum of a contracting PMS star is conserved (i.e., j = const.) the star will spin up as $P \propto R^2$.

Putting together the results above it follows that fully convective low-mass stars spin up as

$$P \propto t^{-2/3} \tag{8}$$

if angular momentum is conserved. In Sect. 3 we estimated that the mean age ratio of stars in NGC 2264 and the ONC is $t_{\rm NGC\,2264}/t_{\rm ONC} \approx 2$. Therefore, if angular momentum is conserved it is expected that the stars in NGC 2264 have on average spun up by a factor of

$$\frac{P(t_{\rm NGC\,2264})}{P(t_{\rm ONC})} = \left(\frac{t_{\rm NGC\,2264}}{t_{\rm ONC}}\right)^{-\frac{2}{3}} \approx 1/1.6 \tag{9}$$

relative to stars in the ONC. This is in agreement with the mean spin-up of 1.5–1.9 derived in Sect. 4.2 by comparing the location of the peaks in the observed period distributions. Note that the spin up indicated by the shift of the peaks is also consistent with age ratios between 1.8 and 2.3.

In summary, the spin up of many NGC 2264 stars relative to the stars in the ONC indicated by the shift of the peaks in the period distributions of the two clusters is consistent with conservation of angular momentum. We note, however, that this conclusion is valid only for the majority of the stars in NGC 2264, since there is evidence that a certain fraction of stars in NGC 2264 (about 30% of the higher mass stars, see below) maintain a lower rotation rate even as they have aged from the ONC (see Fig. 4). These stars are probably still locked to their disks and therefore still lose angular momentum, or have been locked to their disk until recently and have lost considerable amounts of angular momentum during the locking phase (see below).

4.4. Angular momentum loss by magnetic star-disk interaction

Usually the rotational evolution of PMS stars is discussed in terms of two "extreme" cases: first by spin up with no angular momentum loss and second by disk-locking at a constant rotation period, and therefore with a high angular momentum loss rate. In the following we will consider an intermediate case between these two extremes. We will argue below that some stars could indeed lose angular momentum but are not locked to their disk at a constant rotation period. Their angular momentum loss rate is expected to be (much) lower than the one achieved in the disk-locking case. We will call this scenario in the subsequent discussion "moderate" angular momentum loss.

This scenario can be understood as follows. Hartmann (2002) argued that disk-locking is not instantaneous and it takes a time ($\tau_{\rm D}$) until disk-locking is achieved. This disk-locking achievement time $\tau_{\rm D}$ is determined by the rate at which angular momentum is removed from the inner disk and is given by

$$\tau_{\rm D} \gtrsim 4.5\times10^6\ {\rm yr}\ f\,\frac{M_{0.5}}{\dot{M}_{-8}} \tag{10}$$

(Eq. (8) in Hartmann 2002), where $M_{0.5}$ is the stellar mass in units of 0.5 $M_\odot$, $\dot{M}_{-8}$ is the mass accretion rate in units of 10^{-8} $M_\odot$ yr^{-1}, and f is the angular velocity of the star in units of the breakup velocity.

Using Eq. (10) for a 0.5 $M_\odot$ star in the ONC with a typical mass accretion rate of 10^{-8} $M_\odot$ yr^{-1} one obtains that disk-locking is not achieved before 0.5 Myr–1 Myr as long as $f \gtrsim 0.1$. These values agree with the observed f values of the fast rotating ($P \approx 2$ days) higher mass stars of $M \approx 0.5$ $M_\odot$ in the ONC (Herbst et al. 2001). For the fast rotating ($P \approx 1$ days) lower mass stars in the ONC, the f values are somewhat larger, i.e. $f \approx 0.65$ for a 0.1 $M_\odot$ star (Herbst et al. 2001). Therefore, the product of f and M in Eq. (10) is approximately constant for the two mass regimes. However, Rebull et al. (2000) report a mass dependence of the mass accretion rate of the ONC stars in the sense that lower mass stars have typically smaller $\dot{M}$.

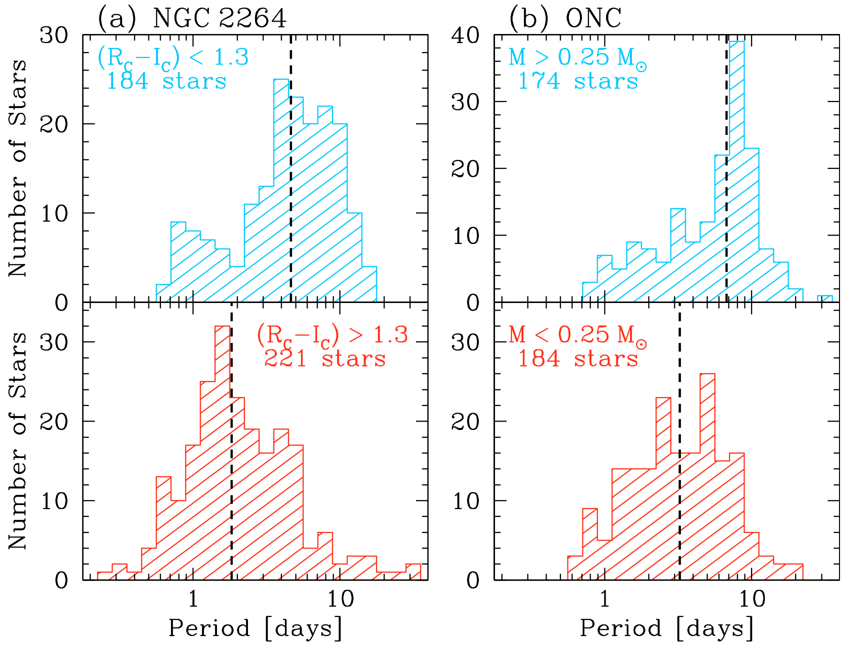

Fig. 4. Same as in Fig. 3 but in logarithmic scale. The dotted vertical lines in each panel represent the median of log(P).

According to their Fig. 24 the mass accretion rate scales approximately as $\dot{M} \propto M^2$ for stars with 0.15 $M_{\odot}$< M < 1 $M_{\odot}$. Hence, the time scale by which disk-locking is finally achieved could be much larger for lower mass stars. Note that this assumes that the magnetic field structure is equal for both mass regimes. As we will discuss in a subsequent paper (Lamm et al. 2004b) it could be that the topology of the magnetic fields of the lower mass stars differs from that of the higher mass stars which could also cause longer disk-locking achievement time scales $\tau_{\rm D}$ for the lower mass stars.

From the estimates of $\tau_{\rm D}$ it is also conceivable that some stars in the ONC (age: ∼1 Myr) have not yet been able to achieve disk-locking. Thus, the presence of fast rotators in the ONC is in principle explainable by disk-locking achievement times which are larger than their ages. Stars with "moderate" angular momentum loss should in principle show similar disk indicators (e.g. large infrared excesses) as stars which already achieved disk-locking. Therefore this scenario could also explain the presence of fast rotating stars with large infrared excesses which were reported by various authors (e.g. Stassun et al. 1999; or Herbst et al. 2002). Since the accretion rate decreases on average with increasing age it is quite conceivable that some stars are unable to achieve disk-locking until the age of NGC 2264.

As also discussed by Hartmann (2002) there is probably a wide range of mass accretion rates in the TTSs phase; i.e. stars with high $\dot{M}$ will be locked within 10^5 yr while others may take 10^7 yr to achieve disk-locking. Also this whole consideration depends strongly on the initial conditions (rotation rate, radius, $\dot{M}$) at which the young star has left the protostellar phase and has entered the TTS phase at the birthline. During the protostellar phase with very high $\dot{M}$ values the star was presumably disk-locked but with a much longer rotation period (see Eq. (15)). In addition one should keep in mind that mass accretion in young stars is a highly variable process on a broad range of time scales; FU Orionis stars are an extreme example for highly variable mass accretion among PMS stars (e.g. Hartmann et al. 2002).

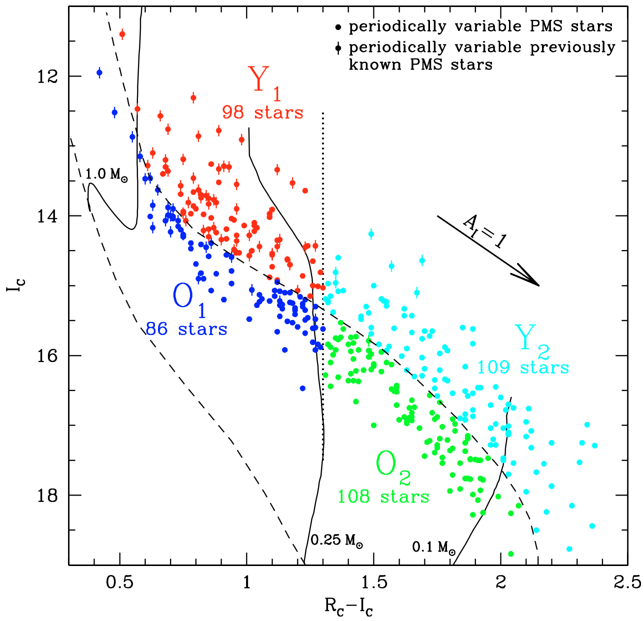

Fig. 5. The colour–magnitude diagram of the periodic variable stars in NGC 2264. The upper dashed and vertical dotted lines define the dividing lines for the four sub-samples Y_1, O_1, Y_2, and O_2. The dotted vertical line at $(R_{\rm C} - I_{\rm C}) = 1.3$ mag (which corresponds approximately to $M = 0.25\,M_{\odot}$) represents the division into higher and lower mass stars. The upper dashed line is a reddened 1 Myr isochrone of D'Antona & Mazzitelli (1997) which we used for a division into younger (Y_1 and Y_2) and older (O_1 and O_2) stars. Reddened 0.1, 0.25, and 1.0 $M_{\odot}$ evolution tracks are shown as solid lines. The number of stars in each of the four sub-samples is also given. The lower dashed line is the ZAMS.

Those stars which interact magnetically with their disks but have ages which are smaller than the disk-locking achievement time scale τ_D are not disk-locked at a constant rotation period (i.e. they are spinning up). However, as long as the magnetic star-disk interaction exists, it continuously removes angular momentum from the stars but at insufficient rates to achieve disk locking. As a result these stars are braked in their spin up (due to contraction) and rotate with periods shorter than the disk-locking period but larger than the periods of stars which spin up conserving angular momentum. This scenario of (magnetically driven) "moderate" angular momentum loss can last as long as the magnetic star-disk interaction exists; i.e., as long as the stellar age is smaller than the dissipation time of the circumstellar disks. It is also feasible that the rotational evolution of a star is first determined by "moderate" angular momentum loss but disk-locking becomes effective later and the star is locked at a fixed rotation period. Also an evolution in the reverse order is possible; i.e., a disk-locked star evolves into a stage of "moderate" angular momentum loss.

4.5. The period distribution in the context of disk-locking

As estimated above NGC 2264 is about twice as old as the ONC. Since we assume that the initial rotation period distributions were similar in both clusters, the period distributions of the ONC represent an earlier evolutionary stage of the rotational properties of PMS stars than the distributions of NGC 2264. In Sect. 4.3 it was shown that the shift of the peaks in the period distributions of NGC 2264 relative to those in the ONC (see Fig. 3) is for many stars consistent with conservation of angular momentum; i.e., the stars which build up the peaks evolve from the ONC to NGC 2264 with constant angular momentum. In the following we discuss the period distributions of NGC 2264 and the ONC in more detail. First, we concentrate on the discussion of the higher mass stars with $M \gtrsim 0.25\ M_\odot$. The lower mass stars will be considered afterwards.

4.5.1. Higher mass stars with $M \geq 0.25\ M_\odot$

In the ONC, Herbst et al. (2002) have interpreted the bimodality of the period distribution of higher mass stars in the range $M > 0.25\ M_\odot$ as an effect of the magnetic interaction of the young stars with their circumstellar disks, i.e., as a result of disk-locking. Based on the observed slow rotators in the ONC (being located in the second peak of the bimodal distribution shown in Fig. 3) they adopted a normal distribution for the locking angular velocity with a mean $\omega_{\rm lock}$ of 0.8 rad/day and standard deviation of 0.2 rad/day (corresponding to $P_{\rm lock} = 7.85^{+2.6}_{-1.6}$ days). In other associations the measured rotation periods of CTTSs also peak at a periods of about 8 days (Bouvier et al. 1997, and references therein). Therefore it is resonable for the further discussion and modelling to adobt an "initial" locking period of about 8 days.

Herbst et al. (2002) made the assumption that the higher mass stars in the ONC located in the second peak of the bimodal distribution shown in Fig. 3 (i.e. all stars with $P \gtrsim 6$ days) are still magnetically locked into co-rotation with their disks or have just been released from them. From the fraction of stars with $P \gtrsim 6$ days they estimated that about 40% of the higher mass stars in the ONC could still be locked to their disks. This interpretation is also supported by measurements of the infrared excess of the stars in the ONC: Herbst et al. (2002) report a (weak) correlation of the infrared excess and the rotation period of the stars in the sense that stars with circumstellar disks rotate with longer periods than stars without disks.

From the upper right-hand part of Fig. 3 it is evident that there is a gap in the period distribution of the higher mass ONC stars with periods between 4 days and 6 days. As we will outline in the following it is very unlikely that the stars with shorter periods (i.e. the stars of the first peak) have ever been magnetically locked to their disk with a period of 8 days. Let us first assume that the stars of the first peak (at 1.5 days) have also been locked to their disks in the past with a locking period of about 8 days and released from their disks at earlier times. Subsequently these stars spun up conserving angular momentum. Using Eq. (9) and adopting a cluster age of 1 Myr, it follows that these stars would have been released from their disks when they were younger than 0.1 Myr and it would have taken about 0.9 Myr to cross the gap in the period distribution. Note that this duration which is needed to cross the gap is a lower limit because angular momentum loss would reduce the spin up. However, as it was shown in the previous section it is very unlikely that the higher mass ONC stars were disk-locked when they were younger than 0.1 Myr, since the time which is needed for these stars to achieve disk-locking (τ_D) is about 0.5−1.0 Myr and may even be longer in some extreme cases. Thus stars in the first peak have probably not had time to achieve disk-locking, then unlocking, and then the substantial spin-up we observe.

Another possibility which could explain the presence of fast rotators (i.e., the first peak) in the period distribution of the higher mass ONC stars is that these stars are locked with a different locking period. However, as it was also shown by Hartmann (2002) locking periods of the higher mass stars which differ (for a given age) by a factor of four are very unlikely (see also Sect. 6.2).

We remind the reader that we assume that NGC 2264 represents a later state in the rotational evolution of the stars; i.e., when NGC 2264 was at the age of the ONC the period distribution of NGC 2264 was identical to those observed today in the ONC. Under this assumption there are two possible explanations for the presence of the second peak in the period distribution of the higher mass stars in NGC 2264:

1. Stars with rotation periods of $P \gtrsim 4$ days are still locked to their disks but the typical locking period $P_{\rm lock}$ in NGC 2264 is generally shorter than that in the ONC. If this is true these stars should show disk indicators such as enhanced Hα emission or infrared excess. As we will see below this is not the case.
2. Stars with $P \gtrsim 4$ days were locked in the past with a locking period similar to the locking period in the ONC and released from their disks presumably when they were at the age of the ONC stars. Now these stars spin up either

conserving angular momentum or with a "moderate" loss of angular momentum. Both would result in a shift of the second peak towards shorter periods (see Sect. 4.3).

Under the assumption that decoupling is a statistical process, one expects that in NGC 2264, compared with the ONC, more of the slow rotators have decoupled from their disks while others are still disk locked at an 8 day period. The shift of the second peak from $P \approx 7.5$ days in the ONC to $P \approx 4$ days in NGC 2264 suggests such decoupling. Further indications are given by the period distributions of the higher mass stars in the ONC and NGC 2264 on a logarithmic scale as shown in the top panels of Fig. 4. According to Eq. (8) log P is a linear function of log t. Therefore, on a logarithmic scale two stars with different initial periods and which spin up with conserved angular momentum do always maintain their distance from each other; i.e., a group of stars which spin up with conserved angular momentum will also conserve the width of their period distribution in Fig. 4. The width of the 8 day peak in the histogram for the ONC is much smaller than the width of the corresponding peak in NGC 2264 which extends between 3 and 12 days. This clearly indicates that a certain fraction of stars does not spin up and is still disk-locked, while the stars with shorter periods have spun up. The number of stars with long rotation period (i.e., $P \gtrsim 6.5$ days) indicates that about 30% of the stars in NGC 2264 could still be locked to their disks.

4.5.2. Lower mass stars $M \geq 0.25\ M_{\odot}$

As already outlined above in Sect. 4.3 most stars in NGC 2264 seem to spin up with conserved angular momentum. This spin up is indicated by a shift of the period distribution peaks to shorter values (see Fig. 3), which are in good agreement with theoretical expections. Additional indications for angular momentum conservation for many low-mass stars in NGC 2264 are provided by the widths of the period distribution on a logarithmic scale, as is illustrated in Fig. 4. It is quite remarkable that in this figure the width of the distribution of the lower mass stars is very similar in both clusters. Why does this strongly suggest that most low-mass stars conserve angular momentum when evolving from the age of the ONC to the age of NGC 2264 (provided the initial conditions are the same)? The arguments for that are the following: In the presence of disk-locking (and therefore angular momentum loss) for a sizable fraction of low-mass stars, the period distribution in Fig. 4 should widen and should not stay constant, because those stars being disk-locked would stay at a constant period (i.e. the right hand side of the distribution would stay at the same value), while those stars conserving their angular would shift to the left. The outcome of that would be a widening of the whole distribution, which is not observed.

There is a pronounced peak between 1.5 days and 2 days in the histogram of NGC 2264 in Fig. 4. Such a peak is not present in the histogram for the ONC where the logarithmic period distribution seems to be more flat. This could indicate that spin up of some lower mass stars but with "moderate" angular momentum loss has happened; i.e. without this braking one would observe more stars with $P \leq 1.5$ days.

In the following sections we investigate whether there is further evidence for the interpretation of the period distributions we suggest here or if other explanations are possible. In addition, the period distribution in the ONC has recently been interpreted by Barnes (2003) as a result of different rotational morphology and a resulting different magnetic structure of the stars which he called the "convective sequence" and the "interface sequence". We will discuss this aspect in a subsequent paper (Lamm et al. 2004b) in more detail where we also investigate the dependence of the peak-to-peak variation on the rotation period.

5. Young and old PMS stars in NGC 2264

In the previous section we found evidence that the spin-up of many PMS stars from the age of the ONC (1–1.5 Myr) to the age of NGC 2264 (2–4 Myr) can be described by conservation of angular momentum. This is in particular the case for the lower mass stars. In this section we investigate whether a similar result can be found using only stars in NGC 2264. Therefore, the period distributions of sub-samples of the cluster stars with different mean ages will be compared.

Each of the two samples of higher and lower mass PMS stars defined in Sect. 4 was divided into two sub-samples of younger and older stars (see Fig. 5). A star was classified as young or old according to its location relative to a reddened 1 Myr isochrone of the DM97 model in the $I_{\rm C}$ vs. $(R_{\rm C} - I_{\rm C})$ colour–magnitude diagram shown in Fig. 5. Stars above and below the 1 Myr isochrone are called young and old stars, respectively. The four different sub-samples are indicated in Fig. 5 by different symbol colours.

In this way the higher mass stars with $(R_{\rm C} - I_{\rm C}) < 1.3$ mag were divided into the two sub-samples Y_1 and O_1 with 98 young and 86 old stars, respectively. Correspondingly the lower mass stars with $(R_{\rm C} - I_{\rm C}) > 1.3$ mag were divided into the two sub-samples Y_2 and O_2 which contain 109 young stars and 108 old stars, respectively. 4 stars with $(R_{\rm C} - I_{\rm C}) > 2.5$ mag were excluded from the analysis.

5.1. Spatial distribution of young and old stars

We first investigate the spatial distribution of the stars in the four sub-samples. Figure 6 shows the spatial positions of the young and old stars separately. It is evident that the younger stars in the upper panels of Fig. 6 show a stronger spatial concentration compared with the older stars in the plots of the lower row. For Y_1 and Y_2 there are two concentrations apparent which we called NGC 2264 N and NGC 2264 S in Paper I. These two concentrations were already mentioned by Sagar et al. (1988) as points of maximum stellar density. The northern concentration is near the O7 Ve star S Mon which is the most massive star in the cluster.

The larger spatial scatter of the older stars in both mass regimes is consistent with the theory that stars form in compact clouds and migrate from their birthplace with increasing age. If we assume a distance of 760 pc (Park et al. 1997) for NGC 2264 a star with a projected tangential velocity of

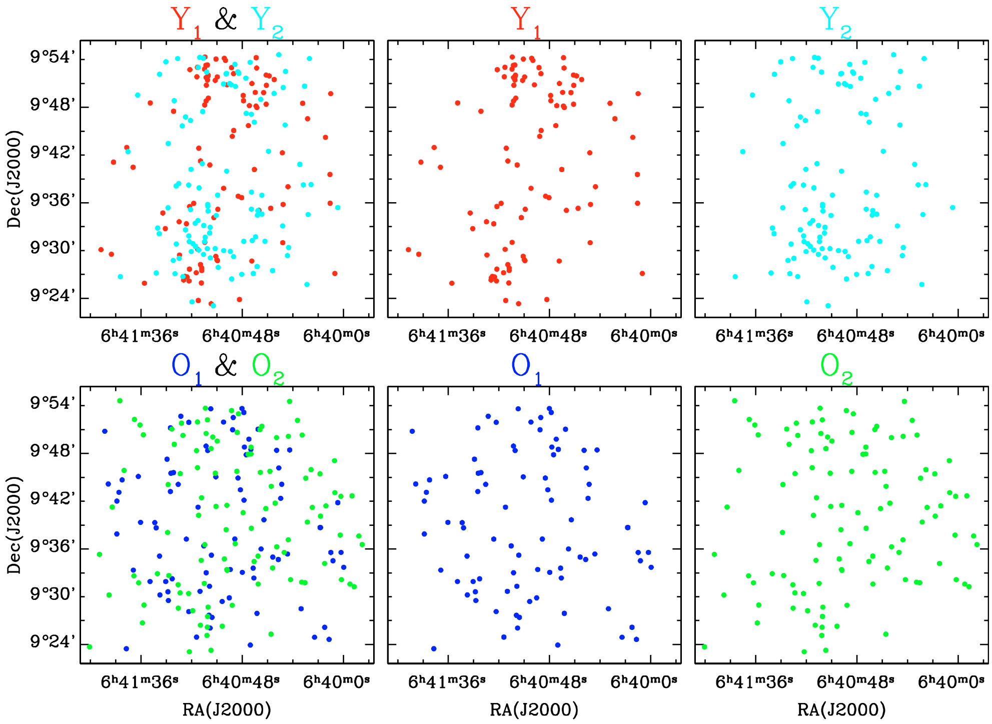

Fig. 6. *Top panels*: the spatial positions of young stars NGC 2264. The left panel shows the positions of the combined sub-samples Y_1 and Y_2 (young lower and higher mass stars) while the middle and right panels show the positions of the stars in Y_1 and Y_2 separately. The colours are the same as in Fig. 5. *Bottom panels*: the same as in the upper row but for old stars in the two sub-samples O_1 (higher mass stars) and O_2 (lower mass stars).

1 km s^{-1} moves 4.5′ within 1 Myr. The observed velocity dispersion of cluster members in the proper motion study by Vasilevskis et al. (1965) is somewhat larger. For the stars with a cluster membership probability of more than 0.95 they observed a dispersion (one sigma) in the proper motions per century (μ_x, μ_y) of 0.″15 and 0.″16 for μ_x and μ_y respectively which corresponds to 25′ per 1 Myr. Therefore, the larger scatter of the older stars could be explained by the migration of the stars with a typical projected velocity of a few km s^{-1} on a time scale of a few Myr.

When comparing the spatial distributions of the subsamples Y_1 and Y_2 in Fig. 6 there is a tendency that the higher mass stars in Y_1 are more concentrated than the lower mass stars in Y_2. This could be a result of a higher tangential velocity of the lower mass stars.

From the left hand panels of Fig. 6 it is also evident that both concentrations of PMS stars in NGC 2264 (i.e. NGC 2264 N & S) contain young and old stars. Therefore there is no evidence for an age difference between these two concentrations, i.e. star formation in the two concentrations happened roughly at the same time.

5.2. Period distribution of young and old stars

Figure 7 shows the histograms of the period distribution on a logarithmic scale for each of the four different sub-samples Y_1, Y_2, O_1, and O_2. Note that the upper left histogram of Fig. 4 (period distribution of higher mass stars in NGC 2264) is the sum of the two histograms for Y_1 and O_1. The lower left histogram of Fig. 4 is the sum of the histograms for Y_2, O_2.

In Sect. 4 we found that the lower mass stars rotate on average faster than the higher mass stars. This result is also apparent from Fig. 7. For both young and old stars the median period (indicated by the dashed lines) is larger for the higher mass stars compared with the lower mass stars in the corresponding sub-sample; for young stars we find that the median period of the higher mass stars (Y_1) is 4.5 days while it is 1.7 days for the young lower mass stars (Y_2). For the older stars we obtain a similar result: the median period of the higher mass stars (O_1) is 5.15 days while it is 1.9 days for the lower mass stars (O_2). Hence, the lower mass stars in both age regimes (i.e. young and old) rotate on average by a factor of 2.7 faster than the higher mass stars in the corresponding sub-sample.

Surprisingly there is no evidence for a spin-up of the older stars in NGC 2264 compared with the younger stars. In contrast the median periods for both the lower and the higher mass stars are even slightly shorter for the younger stars.

A Kolmogorov-Smirnov test (Press et al. 2002), however, yields a probability of 0.4 that the distributions Y_1 and O_1 are equivalent; i.e. they are not significantly different. For the lower mass stars this test indicates that there is only a probability of 4×10^{-3} that the distributions Y_2 and O_2 are equivalent, i.e. the two distributions are significantly different. This difference is also evident from the fraction of fast (and slow) rotating stars in the two samples. For the lower mass stars the fractions of fast rotating stars with periods shorter than 1.3 days are 37% and 17% for the younger and older stars, respectively.

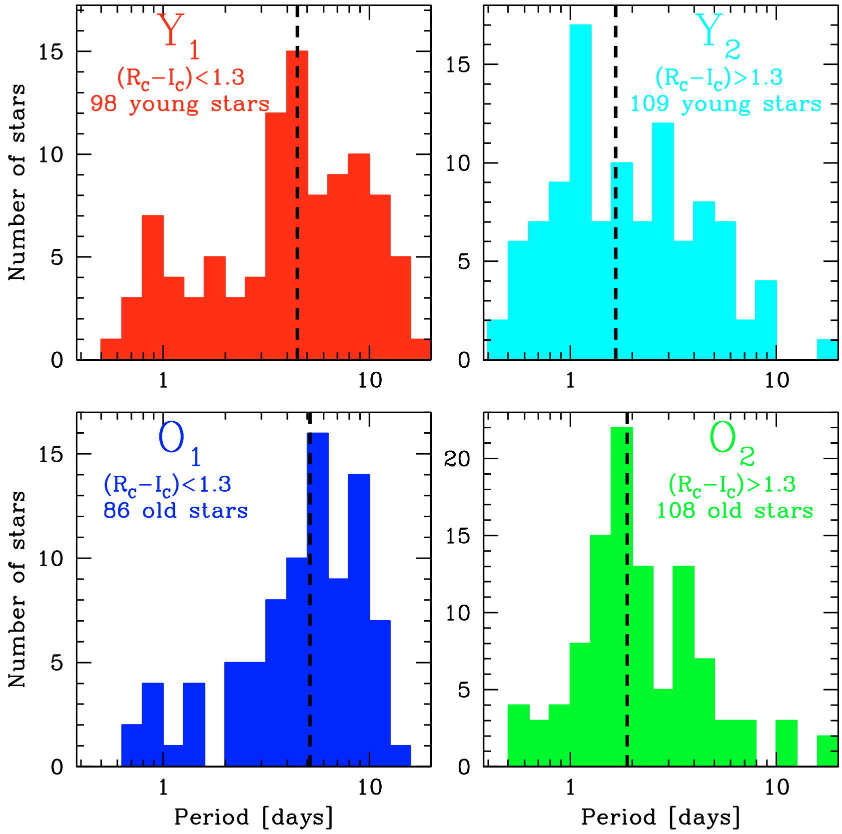

Fig. 7. The period distribution of stars in the four sub-samples Y_1, Y_2, O_1, and O_2 on logarithmic scale. The colours are the same as in Fig. 5. The histograms for higher mass stars are on the left hand side while the histograms for lower mass stars are on the right hand side. The vertical dashed lines indicate the median period for each sample.

In summary, for the lower mass stars we find that the fraction of fast rotating stars is higher for the younger stars. *This is the opposite from what one would expect from a contracting PMS model*. In such a scenario the older stars should rotate with shorter rotation periods than the younger stars if the stars spin up with conserved angular momentum according to $P \propto t^{-2/3}$.

We have no satisfactory explanation for this unexpected behaviour. A possible (and probably the most likely) reason could be that the age spread of the stars is not as big as it is indicated by the scatter of the stars in the colour–magnitude diagram (Figs. 5 and 1) or that the identified young stars are contaminated with old stars and vise versa. A further reason for the enhanced scatter could be the variability of the stars. This interpretation is supported by the fact that the irregular variables which show typically larger brightness variations than periodic variables (see Paper I) also show a larger scatter in the colour–magnitude diagram (see Fig. 12 of Paper I). An additional reason for a misleading age determination of the fast rotating stars could be a large fraction of non-resolved binary stars. This would lead to brighter absolute magnitudes of the variables which results in a younger estimated age. In this scenario the fast rotating young stars would actually be fast rotating older binary stars.

Despite the possible contamination of the young subsample with older stars (and vice versa) and a much smaller age difference than indicated by the colour–magnitude diagram it is quite likely from the spatial distribution of the stars (see Sect. 5.1) that the stars in the sub-samples Y_1 and Y_2 are indeed *on average* younger than the stars in the sub-samples O_1 and O_2.

6. Disk-locking in NGC 2264

In this section we investigate what fraction of the periodic variables in NGC 2264 show evidence for the presence of disk-locking.

6.1. The Hα emission as a disk-locking indicator

In the disk-locking scenario described for example by Shu et al. (1994), angular momentum is transported via magnetic field lines from the PMS star to the circumstellar disk which loses angular momentum via a disk wind. A common feature of the models is the presence of mass accretion onto the star. It is generally believed that large Hα emission equivalent widths (i.e., $W_\lambda(\mathrm{H}\alpha) > 10$ Å) are a result of the increased mass accretion onto the star (e.g. Cabrit et al. 1990; Calvet & Hartmann 1992; Muzerolle et al. 2001).

In order to verify the disk-locking scenario, other authors (e.g. Herbst et al. 2002) looked for a correlation between the rotation period and the infrared excess of the stars as a disk indicator. For the ONC there is evidence that slow rotators have on average a larger infrared excess than fast rotors and Herbst et al. (2002) interpreted this as evidence for disk-locking. However, in their study they also report about rapidly rotating stars with large $(I - K)$ excesses and slow rotators with small infrared excesses.

The drawback of an infrared excess as a disk (and gas) indicator is the following: a large infrared excess is an indicator for the presence of circumstellar dust but it is not necessarily an indicator for current mass accretion. Therefore, even if some ONC stars have large infrared excesses they do not necessarily have high mass accretion rates and may therefore not be locked to their disk. Therefore the presence of strong Hα emission is probably a better indicator for *ongoing* disk-locking. Fortunately there is no strong nebular Hα emission in NGC 2264 which is a serious difficulty in the ONC and prevents accurate determination of the stars' Hα emission in the latter cluster.

Since chromospheric activity of the stars can also produce significant Hα emission the presence of such emission is not a unambiguous sign of mass accretion in particular close to an Hα emission equivalent width of $W_\lambda(\mathrm{H}\alpha) = 10$ Å. Therefore, in the ideal case both indicators – large infrared excess *and* large Hα emission – should be used for the selection of disk-locked stars. However, because of the lack of spectra and spectral types for a large fraction of periodic variables in NGC 2264, Hα emission equivalent widths and infrared excesses are only available from the literature for a small subsample of these stars. Therefore we have to deal here with a photometric determination of the Hα emission based on CCD images obtained through an Hα and a R-band filter (see Paper I for details).

6.1.1. The Hα emission index $\Delta(R_C - \mathrm{H}\alpha)$

In order to investigate the Hα emission of the stars in the two subsamples (i.e. higher and lower mass stars) we use the $(R_C - \mathrm{H}\alpha)$ colour of a star to define an Hα emission index $\Delta(R_C - \mathrm{H}\alpha)$ by the following equation:

$$\Delta(R_C - \mathrm{H}\alpha) = (R_C - \mathrm{H}\alpha)_{\mathrm{star}} - (R_C - \mathrm{H}\alpha)_{\mathrm{locus}}, \quad (11)$$

where $(R_C - \mathrm{H}\alpha)_{\mathrm{star}}$ is the measured colour of the star. $(R_C - \mathrm{H}\alpha)_{\mathrm{locus}}$ is the PMS/MS locus in the $(R_C - \mathrm{H}\alpha)$ vs. $(R_C - I_C)$ colour–colour diagram which was defined in Paper I by Eq. (6). It is also shown in Fig. 9 as a solid line. The Hα-index is a measure of the Hα emission of a star and corresponds to the vertical distance of the star from the PMS/MS locus in $(R_C - \mathrm{H}\alpha)$ vs. $(R_C - I_C)$ colour–colour diagram.

In order to correlate the Hα-index with the Hα emission equivalent width $W_\lambda(\mathrm{H}\alpha)$ of a star we used the full-width at half-maximum of the transmission curves of the applied R_C and Hα filters (1620 Å and 70 Å, respectively) and estimated that equivalent widths of $W_\lambda(\mathrm{H}\alpha) = 10$ Å corresponds approximately to Hα-indices of 0.1 mag. Therefore, stars with large Hα emission (i.e. possible disk-locked stars) were selected if their Hα-index is larger than 0.1 mag, i.e. if

$$\Delta(R_C - \mathrm{H}\alpha) \geq 0.1. \quad (12)$$

To simplify matters we call these stars CTTSs in the subsequent discussion although this specific PMS nature of the stars is not really proven by our analysis because the Hα-index is only an approximate determination of $W_\lambda(\mathrm{H}\alpha)$. However, the stars selected in this way most likely show the properties of accreting PMS stars. Stars that failed the selection criterion of Eq. (12) are called WTTSs for the moment.

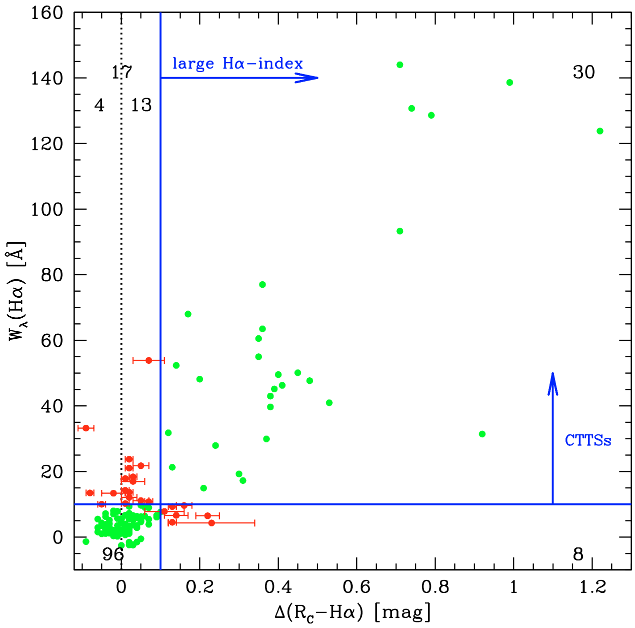

Fig. 8. The Hα emission equivalent width $W_\lambda(\mathrm{H}\alpha)$ as a function of the Hα-index $\Delta(R_C - \mathrm{H}\alpha)$ defined by Eq. (11). The blue vertical solid line has been placed at $\Delta(R_C - \mathrm{H}\alpha) = 0.1$ mag which represents our selection criterion for stars with large Hα emission (i.e. CTTSs). The blue horizontal solid line at $W_\lambda(\mathrm{H}\alpha) \geq 10$ Å represents the classification of CTTSs commonly used in the literature. The vertical dotted line has been placed at $\Delta(R_C - \mathrm{H}\alpha) = 0$ mag and divides stars classified as WTTSs and "intermediate" cases. The number of stars in each of the four quadrants defined by the solid lines are also given. Green symbols indicate that the classification of the stars agrees for both methods, while red symbols represent disagreement. For the latter stars also the photometric error $\delta(R_C - \mathrm{H}\alpha)$ in the $(R_C - \mathrm{H}\alpha)$ colour is indicated.

6.1.2. Comparison of $\Delta(R_C - \mathrm{H}\alpha)$ with the Hα emission equivalent width

In order to verify the classification of CTTSs and WTTSs according to Eq. (12) we compared the spectroscopically measured Hα emission equivalent widths $W_\lambda(\mathrm{H}\alpha)$ of 151 (not necessarily periodically variable) TTSs from Rebull et al. (2002a) with our calculated Hα-index of these stars. In Fig. 8 we show $W_\lambda(\mathrm{H}\alpha)$ as a function of $\Delta(R_C - \mathrm{H}\alpha)$ for all stars in this test sample. Stars with large Hα emission according to Eq. (12) are located right of the blue vertical solid line in this diagram while the stars with $W_\lambda(\mathrm{H}\alpha) \geq 10$ Å are located above the blue horizontal solid line. These latter stars are CTTSs according to the commonly used definition.

The two blue solid lines divide the plane of the diagram in Fig. 8 into four quadrants. Both the Hα emission equivalent width and the Hα-index selection criterion suggest that the 30 stars in the upper right and 96 stars in the lower left quadrant are CTTSs and WTTSs, respectively (green symbols); i.e. the classifications resulting from the two different criteria agree for 126 stars (83.4%). However, there are 25 stars in the upper left or lower right quadrant (red symbols) for which the classifications do not match. Since there are only 8 stars (5.3%) for which the Hα-index criterion suggests a classification as CTTSs but the stars are WTTSs according to $W_\lambda(\mathrm{H}\alpha)$ measurement we conclude that the fraction of erroneously classified CTTSs is negligible. The minimum equivalent width of these false detected CTTSs in the test sample is $W_\lambda(\mathrm{H}\alpha) = 4.3$ Å. We note that variability of the stars will probably be responsible for some of the mismatch between $W_\lambda(\mathrm{H}\alpha)$ and the Hα-index $\Delta(R_\mathrm{C} - \mathrm{H}\alpha)$, since the spectroscopic and photometric data were not taken simultaneously.

There are 17 stars (11.3%) in the upper left quadrant, i.e. these stars are CTTSs according to the $W_\lambda(\mathrm{H}\alpha)$ measurement but are classified as WTTSs according to the Hα-index. Most of these stars (13) are located right of the dotted line, i.e. they have positive Hα-indices. In order to account for this relatively large contamination of selected WTTSs with stars that are actually CTTSs we introduce a new classification of stars which we call "intermediate cases" and which is defined in the following section.

6.1.3. Classification of CTTSs, WTTSs and "intermediate cases"

In the subsequent discussion stars are called WTTS only if

$\Delta(R_\mathrm{C} - \mathrm{H}\alpha) + \delta(R_\mathrm{C} - \mathrm{H}\alpha) \leq 0.0$ mag,

where $\delta(R_\mathrm{C} - \mathrm{H}\alpha)$ is the photometric error of the $(R_\mathrm{C} - \mathrm{H}\alpha)$ colour. In addition stars are called CTTSs only if

$\Delta(R_\mathrm{C} - \mathrm{H}\alpha) - \delta(R_\mathrm{C} - \mathrm{H}\alpha) \geq 0.1$ mag.

The stars which are neither CTTSs nor WTTSs according to these definitions are called "intermediate cases". Figure 9 shows the location of these three samples in the $(R_\mathrm{C} - \mathrm{H}\alpha)$ vs. $(R_\mathrm{C} - I_\mathrm{C})$ colour–colour diagram. According to the above definition stars are only called CTTSs if they are located more than their photometric error $\delta(R_\mathrm{C} - \mathrm{H}\alpha)$ above the dotted line (which represents a Hα-index of 0.1). Analogously, stars are called WTTSs only if they are located more than their photometric error below the solid line, i.e. below the PMS/MS locus with zero Hα-index. This explains the presence of crosses (intermediate cases) above and below the lines in Fig. 9.

Since the photometric errors for stars with $(R_\mathrm{C} - I_\mathrm{C}) \geq 2.1$ mag (i.e. stars later than M6) are relatively large and the PMS/MS locus is poorly defined in this magnitude range, only stars with $(R_\mathrm{C} - I_\mathrm{C}) \leq 2.1$ mag are considered for the further analysis. Of these 381 stars with $(R_\mathrm{C} - I_\mathrm{C}) \leq 2.1$ mag we classified 68 stars as CTTSs, 109 stars as WTTSs, and 204 stars as intermediate cases.

6.2. The dependence of the period distribution from the Hα-index

In this section we present and discuss the period distributions of the different sub-classes of PMS stars (CTTSs, WTTSs, and "intermediate cases") defined in the previous section. According to the standard model, disk-locking is always connected with ongoing accretion onto the star. Therefore, it is expected that most CTTSs (not WTTSs) are locked to their disks.

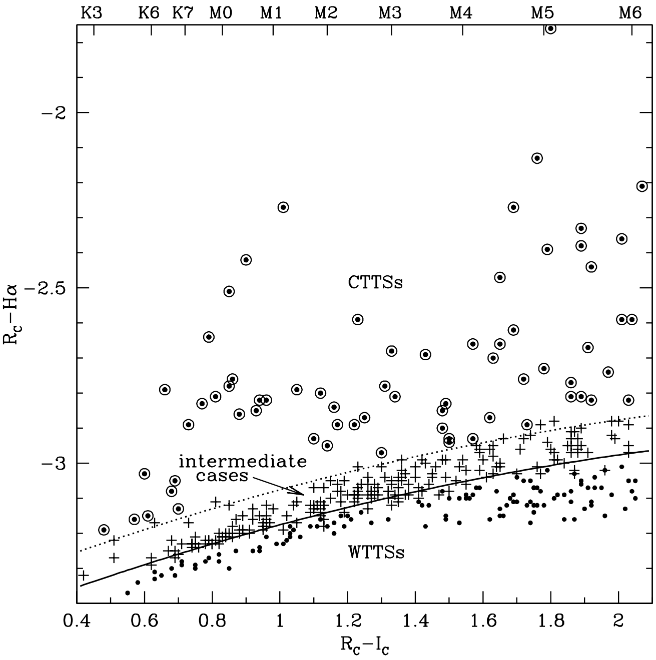

Fig. 9. The $(R_\mathrm{C} - \mathrm{H}\alpha)$ vs. $(R_\mathrm{C} - I_\mathrm{C})$ colour–colour diagram of all 405 periodic variables. The classification of periodic variable CTTSs (⊙), WTTSs (•), and "intermediate cases" (+) was done according to the location of the stars in this diagram. The solid line represents the PMS/MS locus. The dotted line represents a Hα-index of $\Delta(R_\mathrm{C} - \mathrm{H}\alpha) = 0.1$ mag. Only stars which are located more than their photometric error $\delta(R_\mathrm{C} - \mathrm{H}\alpha)$ above that line were classified as CTTSs while stars which are located more than $\delta(R_\mathrm{C} - \mathrm{H}\alpha)$ below the solid line were classified as WTTSs. All other stars are classified as intermediate cases.

However, the presence of accretion and corresponding strong Hα emission is only evidence for angular momentum transfer at the present time; it does not indicate that a star has been locked in the past, or, indeed, that it Is locked even now (see discussion above on disk locking achievement times). Also, stars with sporadically high, but mostly low accretion rates might sometimes have strong Hα emission without being disk-locked. In addition we have to keep in mind that strong Hα emission due to chromospheric activity can lead to false interpretations, in particular for the "intermediate cases".

Figure 10 shows the period distributions for higher mass stars with $(R_\mathrm{C} - I_\mathrm{C}) < 1.3$ mag (in total 184 stars, top panels) and lower mass stars with $(R_\mathrm{C} - I_\mathrm{C}) > 1.3$ mag (197 stars, bottom panels) in the three samples separately. Figure 11 shows the cumulative period distributions of the higher and lower mass stars but only for CTTSs and WTTSs.

It is evident that the period distribution of the higher mass CTTSs looks quite different from that of the WTTSs although the statistics are poor. According to a (binning independent) Kolmogorov-Smirnov test (Press et al. 1992) there is only a probability of 0.02 that the two distributions are equivalent. From Fig. 10 it is also evident that in both mass regimes the CTTSs rotate with longer periods on average than the WTTSs.

The period distribution of the higher mass CTTSs in the upper left hand panel of Fig. 10 is relatively flat compared with that of the WTTSs in the upper right hand panel. This

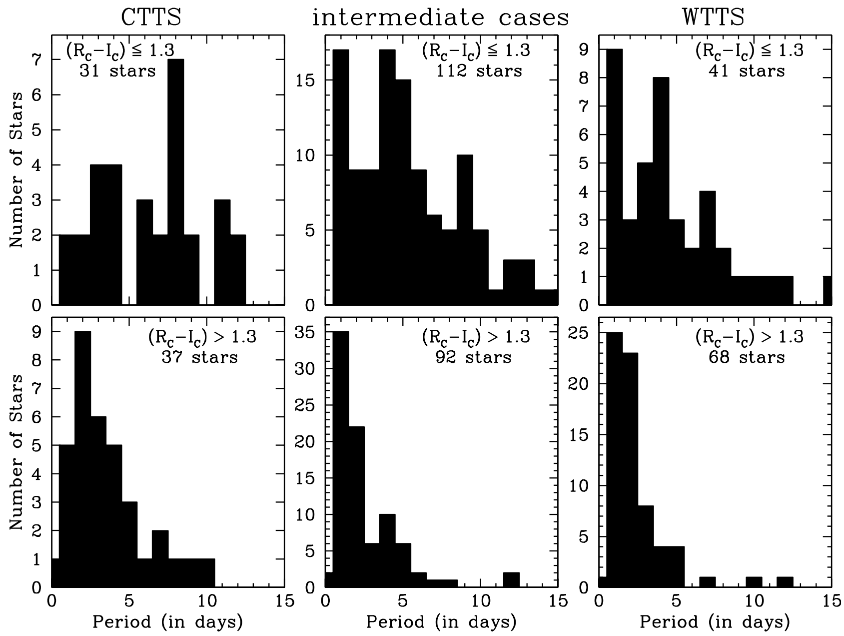

Fig. 10. The period distributions for the three different subclasses of PMS stars (i.e. CTTSs, "intermediate cases", and WTTSs) shown in Fig. 9. Each of these subsamples is divided into higher mass stars with $(R_C - I_C) \leq 1.3$ mag (top panels) and lower mass stars with $(R_C - I_C) > 1.3$ mag (*bottom panels*). The colours are the same as in Fig. 9

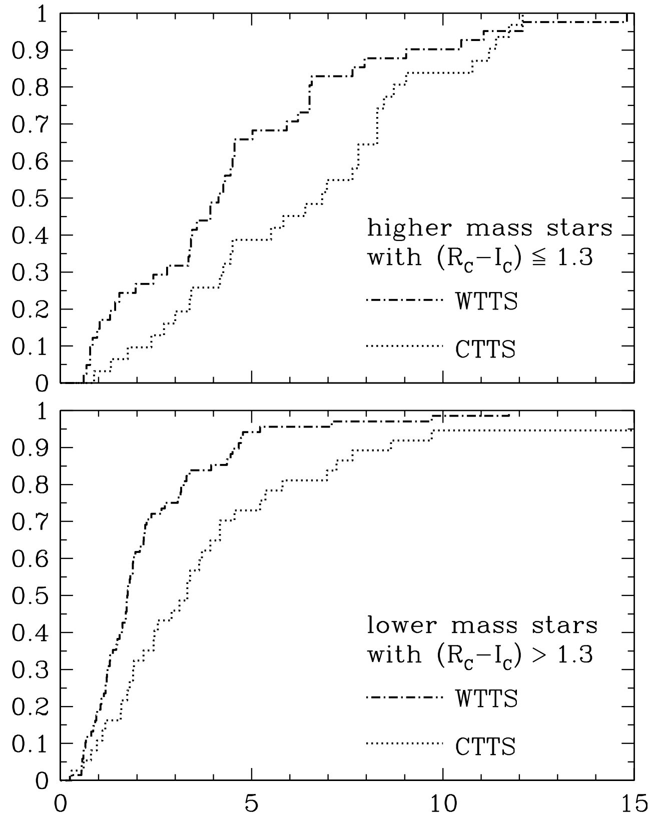

Fig. 11. The cumulative period distribution for CTTSs and WTTSs. The top panel shows the distributions for higher mass stars with $(R_C - I_C) \leq 1.3$ mag while the lower panel shows the distributions for lower mass stars with $(R_C - I_C) > 1.3$ mag.

shows that the (few) CTTSs in NGC 2264 which could be still disk locked show a different period distribution than the stars without disks. In addition the period distribution of the CTTSs apparently shows a peak at 8 days, a noteworthy agreement with the commonly adopted locking period of these stars (see Sect. 4.5). There are also a few CTTSs with rotation periods shorter than 5.5 days. These stars could be either locked CTTSs with a shorter locking period or CTTSs which spin up with "moderate" angular momentum loss.

Let us now discuss the lower mass stars. The period distributions of the lower mass stars (lower panels in are Fig. 10) show an evolution sequence from the CTTSs via the intermediate cases to the WTTSs in the sense that the width of the distributions decreases from the left hand to the right hand panel. This also indicates that WTTSs rotate faster on average than CTTSs. A Kolmogorov-Smirnov test results in a probability of less than 0.001 that the distributions for the CTTSs and WTTSs are equivalent.

One interesting difference between the higher and lower mass stars is that the period distribution of the lower mass CTTSs peaks at about 2–4 days. The possible reason for this finding could be a shorter locking period of the lower mass stars compared with the higher mass stars. If this would be true the locking period for lower mass stars would be about 2–4 days rather than 8 days. This would explain the lack of the 8 day peak in the period distributions of the lower mass stars in Fig. 3. However, we have already mentioned before that such short locking-periods for lower mass stars are questionable. Therefore, we investigate in the following the idea of different locking periods of the higher and lower mass stars in more detail.

According to the model of Shu et al. (1994), the locking period P_{lock} of a given star depends on the stellar mass (M), radius (R), mass accretion rate ($\dot{M}$), and surface magnetic field strength (B). In their model $P_{\rm lock}$ is equal to the Keplerian period, $P_{\rm K}$ of the inner disk, which is truncated at a radius $R_{\rm T}$, i.e.

$$P_{\rm lock} = P_{\rm K}(R_{\rm T}) \propto \left(\frac{R_{\rm T}^3}{M}\right)^{1/2}. \tag{13}$$

With the usual assumption that the stellar magnetic field has a closed global structure which can be modelled approximately by an aligned dipole magnetic field with surface strength B (Königl 1991) the truncation radius is given by

$$R_{\rm T} \propto \left(\frac{B^4 R^{12}}{M\dot{M}^2}\right)^{1/7}. \tag{14}$$

Inserting Eq. (14) into Eq. (13) we obtain for the locking period

$$P_{\rm lock} \propto \frac{B^{6/7} R^{18/7}}{M^{5/7}\dot{M}^{3/7}} \tag{15}$$

(e.g. Shu et al. 1994).

Although very little is known in particular about $\dot{M}$ and B, there is evidence for a power-law mass dependence of $\dot{M}$ on M in NGC 2264 (Rebull et al. 2002a) and the Orion flanking fields (Rebull et al. 2000). According to these studies the mass accretion scales as $\dot{M} \propto M^{\gamma}$ with $\gamma \approx 2$. In addition it would be surprising if lower mass stars have a much weaker magnetic field B than the higher mass stars because they rotate much faster. If one therefore assumes that the locking period depends only weakly on B for a mass range of 0.1–0.3 $M_{\odot}$ and $\dot{M} \propto M^2$ its value is mainly determined by the ratio $R^{18/7}/M^{11/7}$. According to the PMS evolution tracks by D'Antona & Mazzitelli (1997) the stellar radius of lower mass stars at the age of NGC 2264 depends on the stellar mass roughly as $R \propto M^{4/5}$. Using these approximations in Eq. (15) we obtain that the locking period of the lower mass stars in NGC 2264 depends on mass as $P_{\rm lock} \propto M^{18/35} \approx \sqrt{M}$. Using this approximation we find that the locking period of a 0.25 $M_{\odot}$ star is a factor of about $\sqrt{0.25/0.1} \approx 1.6$ larger than the locking period of a 0.1 $M_{\odot}$ star; i.e. the changes in mass, mass accretion rate, and stellar radius without invoking any change of B are not sufficient to explain the suggested changes in locking period.

For higher mass stars there is a weaker mass-radius dependence and therefore also the locking period is less mass dependent. According to the evolution models by D'Antona & Mazzitelli (1997) for stars at the age of NGC 2264 the factor $R^{18/7} M^{-11/7}$ in Eq. (15) varies between a 0.3 $M_{\odot}$ star and a 0.5 $M_{\odot}$ star by 20% but there is basically no mass dependence of this factor for stars with masses larger than 0.5 $M_{\odot}$. Thus the small (1σ) scatter of the locking periods of the higher mass stars of $P_{\rm lock} = 7.85^{+2.6}_{-1.6}$ days adopted by Herbst et al. (2002) may be a result of the small dependence of $R^{18/7}/M^{5/7}$ on mass in this mass range.

As outlined above the locking period of the lower mass stars might be 2–4 days. However, such a short locking period contradicts the corresponding period distribution observed in the ONC where more than half of the low-mass stars rotate with period larger than 3 days. On the basis of our assumption that NGC 2264 is simply an older ONC, one could imagine two different scenarios in the context of "moderate" angular momentum loss for explaining this discrepancy. First, not all stars which interact with their disks at present time and thus have a large Hα-index are indeed locked to their disks at a constant rotation period. Second, "moderate" angular momentum loss controls the rotational evolution of most lower mass stars at the age of the ONC and these stars are unable to achieve disk-locking until they have reached the age of NGC 2264.

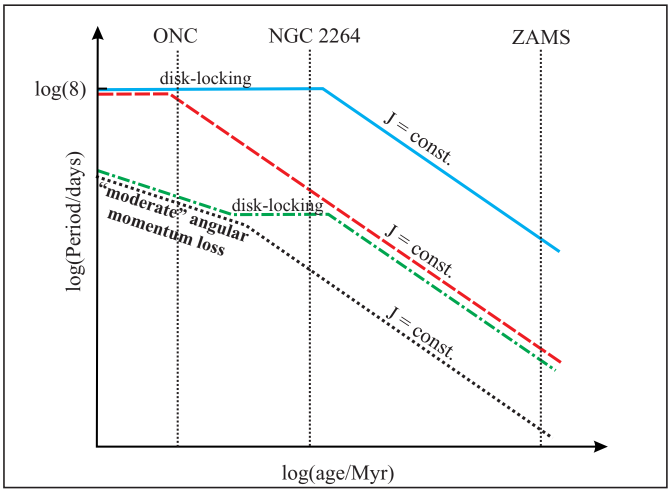

Fig. 12. Schematic diagram of the time evolution of the rotation period for higher and lower mass stars in three different scenarios. The horizontal sections (with P = const.) and right hand sections (with J = const.) of these lines illustrate the two most extreme rotational evolution scenarios, namely disk-locking with constant period and stellar contraction with constant angular momentum ($P \propto t^{-2/3}$). An intermediate case is the so-called "moderate" angular momentum loss, in which the magnetic coupling between the star and the disk is insufficient to enforce disk-locking with constant period, but it is sufficient to achieve some angular momentum transfer from the star to the disk (see text for details).

7. Discussion of possible angular momentum evolution scenarios

In this section we summarise the basic features of the three possible processes, namely disk-locking, "moderate" angular momentum loss, and stellar spin up with conserved angular momentum. These processes may determine the rotational evolution of TTSs. Figure 12 which schematically depicts the different rotational evolution scenarios.

The main result of the previous discussion is that disk-locking is or was present for the higher mass stars in NGC 2264 with $(R_{\rm C} - I_{\rm C}) \leq 1.3$ mag (i.e. $M \geq 0.25$ $M_{\odot}$). The locking period of these stars is likely about 8 days which is suggested by the period distributions in Figs. 3 and 4. Also the period distribution of stars with large Hα-index suggests this locking period.

The solid blue and the dashed red line in Fig. 12 illustrates the two extreme rotational evolution scenarios of disk-locked stars. In both cases the stars are locked with a rotation period of about 8 days. While the first star (blue line) is locked for a longer time (i.e. several Myr) and is still locked at the age of

NGC 2264 the second star (red line) decouples from its disk when it was younger than the ONC stars. After their decoupling the stars spin up in both cases towards the main sequence with (nearly) constant angular momentum since angular momentum loss due to Skumanich-like winds is negligible on the time scales considered here. It was outlined that disk-locking is probably more important for the higher mass stars. The fraction of locked stars depends on the age of the stars and is smaller for older clusters. Comparison of the period distributions of the ONC and NGC 2264 suggested that most of the higher mass stars spin up with conserved angular momentum in this age range. Their rotational evolution is therefore most likely illustrated by the red dashed line.

As it was shown, it is possible to explain the presence of fast rotators among the higher mass stars in the ONC and NGC 2264 (i.e. the first peak in the period distributions) by "moderate" angular momentum loss. The black dotted line in Fig. 12 depicts the rotational evolution of such fast rotators: As long as the stars interact magnetically with their disks they lose some angular momentum but they still spin up with decreasing radius. Once the star-disk interaction breaks down the stars spin up conserving angular momentum.

The three outlined scenarios result in a large scatter of rotation periods at the ZAMS which is observed in several ZAMS clusters (e.g. Bouvier et al. 1997). In order to explain the observed rotation distributions on the ZAMS (in particular the presence of some very slow rotators) disk-locking times of at least 10 Myr are required in a few cases (Barnes et al. 2001).

We concluded that ("perfect") disk-locking may be less important for the rotational evolution of most lower mass stars since most of the lower mass stars apparently spin up from the ONC to NGC 2264. Most of the spin up of these stars can be explained by conservation of angular momentum or "moderate" angular momentum loss. Hence, the fraction of stars with "moderate" angular momentum loss may be larger for the lower mass stars compared with the higher mass stars and only a few lower mass stars may be disk-locked.

Figure 12 illustrates an additional rotational evolution scenario (dashed-dotted green line). In this scenario the star is not able to achieve disk-locking in the early evolution stage but "moderate" angular momentum loss is happening until the star is slightly older than the ONC stars. After that time the star is able to achieve disk-locking. Here the locking period is shorter than the 8 day period. This evolution scenario is in agreement with the analysis of the Hα-index for the lower mass stars. However, we have shown that this shorter locking period is very unlikely.

8. Comparison with the Makidon et al. (2004) data

The main work for this paper was completed in November 2003 by one us as part of his Ph.D. dissertation work (Lamm 2003). It is the second of three papers in a series. In the meantime another paper on the periodicity of PMS stars in NGC 2264 (Makidon et al. 2004; hereinafter M04) appeared in print just after our paper was submitted but before it was refereed. The conclusions reached in that paper are nearly directly opposite to the conclusions reached here. In particular M04 find that the period distribution in NGC 2264 is indistinguishable from that found in the Orion region, and that most stars (70−100%), therefore, do not spin up between Orion age and NGC 2264 age. They also find, contrary to the results reported here, that there is no difference in the rotation properties of stars with and without disk indicators.

In the following we show that despite the fact that the M04 period distribution of their quality 1 data is indistinguishable within the statistical errors from ours, we come to quite different conclusions about the interpretation. We will argue that one major reason for these discrepancies is probably the large inhomogeneity of the "whole" Orion region with which M04 compare their NGC 2264 data, while we compare our NGC 2264 data only with the ONC, which is the youngest and most homogeneous cluster of the Orions OBI association.

Since the focus of this paper and of M04 is on the rotation period distributions we confine our remarks to the portions of these programs aimed at determining such periods. The approaches are the same – monitor the NGC 2264 field and search for periodic variables. The principle differences in the data sets are that ours goes deeper and has a much higher sampling frequency during a more limited time period. It is impossible to quantify this difference because M04 do not give a precise ephemeris for their observations. However, it appears from their Table 1 that their data were obtained on only 18 or 23 nights of observation (depending on which information is correct, that in Cols. 3 or 4), and was highly "clumped", coming in roughly one week intervals separated by one or two months. Our data, by contrast, is concentrated into an intensive 44 night period with an interval of very high sampling rate in the middle (see Fig. 2 of Paper I). That makes it easier for us to determine accurate rotation periods, especially for fainter stars, and we are less susceptible to mistaking beat periods or harmonics for true periods. This in combination with our much deeper images probably accounts for the fact that we find a total of 405 rotation periods in essentially the same field as studied by M04 who report 201 rotation periods.

The period search techniques are similar although not identical but we have no reason to suspect that one or the other is in error. Of the 201 stars reported periodic by M04 we found 113 also to be periodic. M04 divide their stars into two quality classes, that are designated 1 and 2, for higher quality and lower quality respectively. In Fig. 13 we compare the periods reported by M04 with our periods for the 113 stars in common, 67 of which are of quality class 1 (crosses in the figure) and 46 of quality class 2 (boxes). The quality 1 stars match our periods with greater frequency than do the quality 2 stars. We find that 93% (62/67) of the quality 1 stars have identical periods in the two surveys. For the quality 2 stars only 76% (35/46) of the periods match. Most of the mismatches lie along either harmonics or beat periods with one day. Since our light curves have a much better sampling than theirs and since they themselves define their quality 2 periods to be less reliable, we suspect that the periods we report for their quality 2 light curves will be the actual rotation periods in most cases. In general, this comparison of periods from the separate studies is gratifying, especially since our data were obtained several years after theirs,

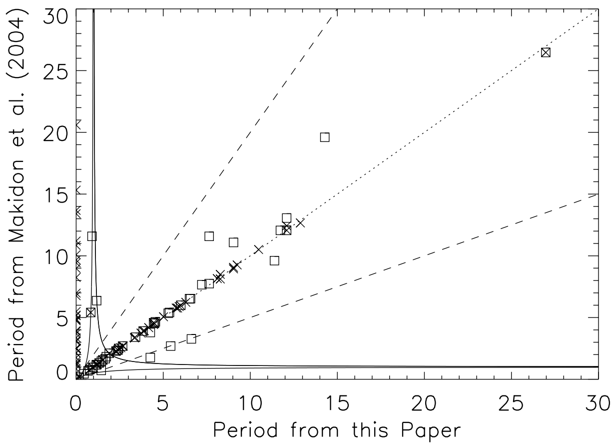

Fig. 13. Comparison of the periods of 113 stars which were measured both by Makidon et al. (2004) and in this paper. Stars with the same period in both studies are located at the doted line. The dashed lines represent harmonics. The solid lines represent beat periods, i.e. a relation of $1/P_{\rm M04} = \mp 1 \pm 1/P$, where $P_{\rm M04}$ and P are the periods found by Makidon et al. and in this study. Crosses mark the 67 quality 1 stars and the boxes the 46 quality 2 stars of the Makidon et al. sample.

and gives us confidence that both studies are indeed measuring (mostly) reliable rotation periods for these stars.

In Fig. 14 we show the period distributions of the M04 sample, divided by $R-I$, for the higher and lower quality classes, respectively. We find that the quality 1 stars with $R-I < 1.3$ bear a remarkable resemblance to our distribution for the same colour range (see Fig. 3a). In particular, there are clear peaks at 1 and 4 days and even a third peak at 8 days. where we find a broad "hump". The quality 2 data set shows much less definition, probably for two reasons. First, there are not that many stars to define the distribution and second, the periods are probably less reliable, as noted above. For the combined quality class distribution for $R-I < 1.3$ one obtains a distribution essentially the same as what is shown in Fig. 6b of M04. A quantitative comparison of our period distribution with the M04 data confirms the visual impression. A Kolmogorov-Smirnov (K-S) test shows that there is a 99.7% probability that our period distribution matches the $R-I < 1.3$ quality 1 period distribution of M04 (i.e. that they were drawn from the same parent population). For the M04 quality 2 stars, the probability is 51.5% that they have the same parent population as our sample. Clearly the data from M04 are entirely consistent with ours, and particularly so if one restricts attention to their quality 1 stars.

Is it possible to understand why M04 reach quite different conclusions than we report here? First, we note that there is no doubt from our sample and little doubt from the smaller M04 sample that the NGC 2264 stars have a significantly different period distribution than the ONC stars. This is evident in our Fig. 3 and it is also evident in the M04 distributions shown here and in Fig. 6b of their paper. The NGC 2264 distribution has a clear concentration of stars with periods near 4 days, which is precisely where the gap in the bimodal distribution of the ONC stars is. We do not understand why this feature was not noticed by M04. Furthermore they do not mention in the text of their paper what is shown in their Fig. 7 (middle panel of left hand side), namely that a K-S test of their data against the ONC reveals that the two distributions are different at the 99% level. In other words, their own data indicates a significant difference between the NGC 2264 period distribution and the ONC period distribution, which is not discussed in the text of their paper.

The expanded data set reported here significantly strengthens the case that the NGC 2264 stars with $R-I < 1.3$ have a significantly different rotation period distribution than the higher mass ONC stars. A K-S test reveals the distributions differ at the 99.9994% level, confirming and strengthening what was already shown by M04 but not discussed in the presentation of their results, except for the middle-left panel of Fig. 7.

What is left to discuss is the very different conclusions reached by these two studies in the light of essentially identical data sets (although ours is admittedly twice as large). Our interpretation of their argument is that M04 do not regard the ONC as a separate entity and concentrate on the entire Orion region to compare the period distributions. They state that there is an age difference between the ONC and NGC 2264 and we agree. They appear to believe that this *same* age difference can be extended to the *whole* Orion region, that includes the "flanking fields" searched for periods by Rebull et al. (2002b) and the larger Orion association surveyed for periods by Carpenter et al. (2001). Their argument appears to be that the radii of stars in this greater Orion region is no different from the ONC and so these stars have a comparably young age. Therefore, the lack of difference in the period distribution between Orion (taken as an aggregate, which tends to diminish the significant ONC discrepancy) indicates no spin-up of stars from "Orion age" to NGC 2264 age.

We think that this line of argument is not correct and leads to the different conclusions which M04 reach. First of all, it ignores the significant difference in period distribution between the ONC and NGC 2264. In our view this difference is simply a reflection of the differing ages and the spin-up due to stellar contraction that has occurred. In their picture it has no easy explanation (and we can only speculate that they ignored this fact). We emphasize again that there is a 99.9994% significance level that the ONC and NGC 2264 period distributions are different. Secondly, we remind the reader of the wealth of data which has shown that the Orion association is composed of several different subgroups with different ages (see e.g. Warren & Hesser 1978). The ONC (also known as Ori OB Id) is widely regarded for solid reasons as the youngest of these. Mixing together a general population of stars across the "whole" Orion is certain to produce a broader period distribution characteristic of a generally older population than the ONC and this, in our view, is why M04 find no difference between "Orion" and NGC 2264.

As already argued in this paper the evidence is rather strong that there is an age difference of about a factor 2 between the ONC and NGC 2264 (see Sect. 3) and in addition there is strong evidence that there is a period distribution difference between these two clusters (see Sect. 4.2). In contrast, the evidence is rather weak that the ONC and the other parts of Orion OBI association share the same extremely young age as argued by M04 on the basis of their radii measurements of individual

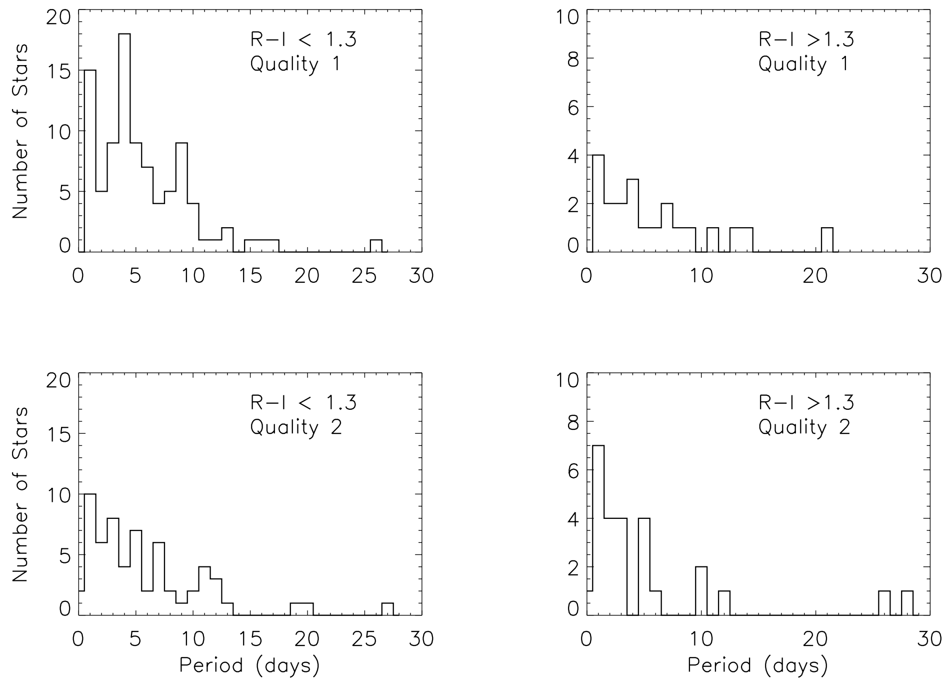

Fig. 14. Period distribution of the Makidon et al. (2004) sample, divided into four subgroups of different colour and data quality. The top two histograms show the period distribution for their quality 1 stars while the two at the buttom show the corresponding histograms for the quality 2 stars. A Kolmogorov-Smirnov test shows that there is a 99.7% probability that our period distribution shown in the upper left-hand part of Fig. 3 matches the $R - I < 1.3$ quality 1 period distribution shown here.

PMS stars. It should be emphasised that determining individual radii is a difficult proposition at best, especially in Orion where variable extinction effects alone can be large (in addition to variability, uncertainties in spectral classification and knowledge of intrinsic colours etc.). As we showed above, when one tries to isolate a particular age group on the basis of the radii of the stars one finds no difference in their rotation period distribution. Rebull et al. (2002b) has shown that this is true for a wide variety of stars in various associations and we confirm the result here for NGC 2264. However, we do not share their interpretation that this means that most stars do not spin up as they contract. We believe it actually means that radii of PMS stars cannot be determined accurately enough to be useful in isolating a group of stars of common age. To do this, one needs other criteria, such as location on the sky within an acknowledged extremely young cluster (i.e. the ONC).

Finally, we note that if one accepts the conclusions of M04 then one is left with the conundrum that 70−100% of the NGC 2264 stars should be still locked to their disks, i.e., most PMS stars in NGC 2264 should be CTTSs instead of WTTSs, as observed. This is hard to understand since a much smaller percentage (~20%) of the PMS stars in NGC 2264 show characteristics typical of CTTSs (i.e. strong Hα emission) and should therefore have accretion rates at levels sufficient for disk locking (cf. Hartmann 2002). If one adopts that the greater Orion association has a large enough age spread and mean age that it can mimic the rotation period distribution in NGC 2264 then there is no longer a need for such a large fraction of disk locked stars.

To summarise, this comparison between our data and M04 reveals the following facts: 1) The periods agree in more than 90% of cases for their quality 1 stars and in a lesser, but still reasonably good percentage of cases (76%) for their quality 2 stars. This confirms that their quality 2 data is of lesser reliability, as they propose. 2) the period distributions for stars with $R - I < 1.3$ are identical for our stars and their quality 1 data and are not significantly different for our stars and their quality 2 data. 3) Their period distribution for the stars with $R - I < 1.3$ differs significantly (at the 99% level) from the distribution of stars with masses >0.25 solar masses in the ONC, as they themselves show in their Fig. 7. Our data strengthen and support that result, increasing the probability that the ONC and NGC 2264 distributions are different to 99.9994%.

Our analysis further clarifies the difference in interpretation between ourselves and M04 lying in the nature of the ONC with respect to other regions of the (inhomogeneous) Ori OBI association. We regard the ONC as a relatively homogeneous cluster of very young (~0.5−1 Myr) age that has significantly more slow rotators than NGC 2264, a fact which can be understood by the difference in age of the clusters (by about a factor 2) and the spin-up of the bulk of the stars as they contract from Orion age to NGC 2264 age, conserving angular momentum. M04 apparently do not believe that there is a significant period distribution or age difference between the ONC and the parts of Ori OBI region surveyed for periodicity by Rebull (2001) and Carpenter et al. (2001). They combine these studies to claim that there is no significant difference in period distribution between "Orion" and NGC 2264. This leads to some untenable conclusions, in our view. It requires that the majority of stars of NGC 2264 age have been disk-locked or otherwise regulated in their rotation period without showing evidence for the mass transfer from a disk which is required to transfer sufficient momentum to do this. On the other hand, our interpretation is that ~80% of the stars in NGC 2264 are NOT regulated, and that is consistent with the high fraction of WTTSs. To populate the 8 day "hump" in the period distribution, we do require some disk-locking, at the level of ~20−30%, which is consistent with the fraction of stars with currently high accretion rates based on our Hα measurements.

9. Summary and conclusions

The results presented in this paper are based on an extensive photometric monitoring program in the young (2–4 Myr) open cluster NGC 2264 which yielded 405 rotation periods of stars. These stars are most likely PMS members of the cluster. The main results of our investigations are as follows:

1. We have estimated that the stars in NGC 2264 are twice as old on average as the stars in the younger open Orion Nebular Cluster (ONC). This estimate is consistent with the commonly adopted cluster ages in the literature which are 1 Myr for the ONC and 2–4 Myr for NGC 2264.
2. We found that the period distribution of NGC 2264 is highly colour dependent. It is bimodal for bluer (i.e. higher mass) stars with $(R_C - I_C) \lesssim 1.3$ mag and unimodal for redder (i.e. lower mass stars with $(R_C - I_C) \gtrsim 1.3$ mag. The colour of $(R_C - I_C) = 1.3$ mag above which the period distribution is unimodal corresponds approximately to a mass of $M = 0.25\ M_\odot$ (according to the PMS evolution models by D'Antona & Mazzitelli, 1997). In addition we found that the lower mass stars in NGC 2264 rotate by a factor of 2.5 faster than the higher mass stars in the cluster.
3. Comparison of the period distribution in NGC 2264 with that of the ONC found by Herbst et al. (2001, 2002) yielded qualitative agreement for both mass regimes. However, the median rotation periods (which are by a factor of 1.5–1.8 shorter in NGC 2264) as well as the shift of the corresponding peaks to shorter periods in NGC 2264 indicates that many stars (i.e. about 80%) spin up from the age of the ONC to the age of NGC 2264.
4. The main assumption for the conclusions we draw in this paper is that NGC 2264 represents a later stage in the rotational evolution of the stars than the ONC: in particular we assumed that the period distribution of the ONC which we observe today was identical to the period distribution of NGC 2264 when it was at the age of the ONC. We have shown that under this assumption and for fully convective, rigid rotating and homologous contracting stars the measured spin up by a factor of 1.5−1.9 is consistent with conservation of angular momentum and shrinking stellar radius. Therefore, many stars seem to spin up from the age of the ONC to the age of NGC 2264, conserving angular momentum.
5. The last conclusion is not valid for all stars in NGC 2264 because a certain fraction of the stars in that cluster (about 30% of the higher mass stars) maintain a longer rotation period even as they have aged from the ONC. Evidence for this is given by the rotation period distribution on a logarithmic scale which shows a broader distribution of the higher mass stars in the case of NGC 2264. This broadening indicates angular momentum loss of some stars and these stars are probably still disk-locked (or have been disk-locked until recently).
6. Depending on the location of the stars above or below an isochrone in the colour–magnitude diagram we have classified stars in NGC 2264 as young or old, respectively. The period distributions of these different subsamples yielded no evidence for a significant spin up of the older stars relative to the younger stars. A possible reason could be that the age classification is poor because of the intrinsic scatter of these stars in the colour–magnitude diagram. The spatial location of the stars in the different subsamples, however, indicate that the stars in the younger sample are indeed younger than the stars in the older sample.
7. We have defined an Hα emission index as a measure of the stars' Hα emission. Based a comparison of measured Hα equivalent width we have defined a classification for three different samples of stars, namely CTTSs, "intermediate cases" and WTTSs. The higher mass stars classified as CTTSs show a different period distribution than the other two classes (i.e. WTTSs and "intermediate cases") of higher mass PMS stars. The peak of the period distribution for the CTTS at about 8 days is in agreement with the commonly adopted locking period.
8. The period distribution of the lower mass stars which are classified as CTTSs also differs significantly from the period distributions of the other two samples of lower mass stars. The interesting difference between the higher and lower mass stars is that the lower mass stars have a peak in the period distribution at 2–3 days. We have argued that it is quite unlikely that this is indeed the locking period of the lower mass stars. We have proposed that a different evolution scenario (which we called "moderate" angular momentum loss) could explain this finding. In this scenario stars lose angular momentum because of the magnetic star-disk interaction but not enough to lock the stars to a constant rotation period. The result is a reduced spin up of the stars.
9. A detailed comparison with the Makidon et al. (2004) paper has shown that their rotation period distribution for NGC 2264 for their quality 1 data (and for stars with $R - I < 1.5$) is practically identical at a 99.7% confidence level with our measured period distribution. We discuss in detail how these authors, despite nearly identical period distributions (except for about half the measured periods), came to quite different conclusions namely that there is no spin up between "Orion" and NGC 2264. We explain this different conclusion by mixing various data from the (inhomogeneous) Orion OBI association into a single "Orion dataset". Restricting a comparison with NGC 2264 only to the ONC (i.e. the youngest cluster in the Ori OBI region) shows a clear difference in the period distributions at a 99.9994% confidence level.

Our analysis has shown that the rotational evolution of the stars is not unique. Although most stars spin up with conserved angular momentum from the ONC to NGC 2264, several different rotational evolution scenarios seem to be important, such as disk-locking and "moderate" angular momentum loss.

The decisive factor for the rotational evolution of the stars with $M \lesssim 2\ M_{\odot}$ is the stellar mass. Higher mass stars (with $M \gtrsim 0.3\ M_{\odot}$) seem to be longer and more frequently disk-locked than lower mass stars (with $M \lesssim 0.3\ M_{\odot}$), while for the latter, "moderate" angular momentum loss appears to be more important. However, our analysis demonstrated that the rotational evolution of stars is not only a question of the stellar mass and whether a star is disk-locked or not.

In order to investigate what fractions of stars follow the the different evolution scenarios more complete data sets of stars in other (i.e. older) clusters are necessary.

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