THE ASTROPHYSICAL JOURNAL, 671:605–615, 2007 December 10

TESTING THE DISK REGULATION PARADIGM WITH *SPITZER* OBSERVATIONS. II. A CLEAR SIGNATURE OF STAR-DISK INTERACTION IN NGC 2264 AND THE ORION NEBULA CLUSTER

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Received 2007 April 16; accepted 2007 July 27

ABSTRACT

Observations of pre-main-sequence star rotation periods reveal slow rotators in young clusters of various ages, indicating that angular momentum is somehow removed from these rotating masses. The mechanism by which spin-up is regulated as young stars contract has been one of the longest standing problems in star formation. Attempts to observationally confirm the prevailing theory that magnetic interaction between the star and its circumstellar disk regulates these rotation periods have produced mixed results. In this paper, we use the unprecedented disk identification capability of the *Spitzer Space Telescope* to test the star-disk interaction paradigm in two young clusters, NGC 2264 and the Orion Nebula Cluster (ONC). We show that once mass effects and sensitivity biases are removed, a clear increase in the disk fraction with period can be observed in both clusters across the entire period range populated by cluster members. We also show that the long-period peak ($P \sim 8$ days) of the bimodal distribution observed for high-mass stars in the ONC is dominated by a population of stars possessing a disk, while the short-period peak ($P \sim 2$ days) is dominated by a population of stars without a disk. Our results represent the strongest evidence to date that star-disk interaction regulates the angular momentum of these young stars. This study will make possible quantitative comparisons between the observed period distributions of stars with and without a disk and numerical models of the angular momentum evolution of young stars.

Subject headings: infrared: stars — open clusters and associations: individual (NGC 2264, Orion Nebula Cluster) — planetary systems: protoplanetary disks

Online material: machine-readable tables

1. INTRODUCTION

For many years, the loss of angular momentum in the evolution of pre-main-sequence (PMS) stars was a fundamental problem in the theory of star formation. As PMS stars contract by a factor of ∼2–3 during their first 3 Myr of evolution, models assuming homologous contraction and conservation of angular momentum dictate that all stars less than $\sim 1.2\ M_{\odot}$ should rotate with periods shorter than ∼2 days by an age of 2 Myr (D'Antona & Mazzitelli 1998; Herbst et al. 2000). However, observations of clusters determined to be ∼2 Myr old or older show that most PMS stars rotate much slower than expected. Interaction between the magnetic field of a young star and the inner regions of its protoplanetary disk has been invoked by virtually every rotational evolution model as the mechanism by which the rotation periods of these stars are regulated as they evolve onto the main sequence (Königl 1991; Shu et al. 1994; Hartmann 2002; Matt & Pudritz 2005).

A first-order prediction of these models is that stars interacting with their disks should have longer rotation periods than stars that have already lost their disks, leaving them free to spin up as they contract (Herbst & Mundt 2005). Early observations of rotation periods of PMS stars, obtained by monitoring the brightness modulation produced by stellar surface features, seemed to support the star-disk interaction scenario for angular momentum regulation.

Some studies showed correlations between rotation period and ground-based disk indicators (most commonly excess *K*-band emission, e.g., Herbst et al. 2002), and the authors interpreted these results as strong evidence for star-disk interaction, claiming that stars with longer periods were rotating more slowly because they had transferred angular momentum to their disks (Edwards et al. 1993; Herbst et al. 2000, 2002; Lamm et al. 2005). This interpretation suffers from several problems as various issues can mask or mimic the correlation, such as sample size, sensitivity biases, mass effects, and, most importantly, ambiguous disk indicators. Therefore, the correlation between infrared (IR) excess and rotation period was challenged by studies which failed to find any correlation between rotation period and a range of disk and accretion indicators in various clusters (Stassun et al. 1999; Rebull 2001; Rebull et al. 2004; Makidon et al. 2004; Littlefair et al. 2005). This paper presents conclusive evidence that star-disk interaction is the mechanism by which PMS angular momentum is regulated.

The ability to overcome the confusion surrounding the angular momentum problem arrived with the acquisition of *Spitzer* mid-IR observations sensitive enough to unambiguously determine the presence of a disk around PMS stars in the Infrared Array Camera (IRAC) bandpasses. In a study of the young cluster IC 348 (Cieza & Baliber 2006, hereafter Paper I), we find that 8.0 μm data are needed to clearly identify all of the disks in a given sample of stars (Paper I, Fig. 5; see also Hartmann et al. 2005; Rebull et al. 2006).

Both the near-infrared (NIR) and IRAC wavelengths trace the inner rim of the disk (Allen et al. 2004; Cieza et al. 2005).

However, since the magnitude of the IR excess over the stellar photosphere is much larger at IRAC wavelengths than it is at NIR wavelengths (e.g., 2MASS [Two Micron All Sky Survey] wavelengths), IRAC observations, unlike ground-based studies, are sensitive enough to unambiguously determine the presence of a disk around PMS stars.

It might be argued that the sensitivity of the 8.0 μm excess allows detection of both active, accreting disks and passive disks which no longer interact with their parent stars. However, the fact that the presence of an IRAC excess does not guarantee that the stars are *currently* accreting does not affect our conclusions for multiple reasons. First, disk dissipation timescales (the time it takes for a given disk to dissipate once it has begun that process) are much shorter than the mean accretion disk lifetimes. For instance, from the ratio of the number of weak-line T Tauri stars (WTTSs) with IRAC excesses to the number of PMS stars (WTTSs plus classical T Tauri stars [CTTSs]), Cieza et al. (2007) estimate the transition timescale from optically thick accretion disks to disks undetectable at IRAC wavelengths to be 0.4 Myr, a factor of $\sim$10 smaller than typical accretion disk lifetimes. This timescale is very similar to the transition timescale between an optically thick disk and an optically thin disk found by Skrutskie et al. (1990) and Wolk & Walter (1996) based on the number of "transition objects," which they define as targets without *K*-band excess but with strong *IRAS* excesses. Thus, if an object currently shows an IRAC excess, it is much more likely than not to be accreting.

Moreover, once star-disk interaction stops, it takes some time for stars to spin up significantly. This "reaction lag time" will tend to compensate for the "detectability lag time" (the time between the end of star-disk interaction and the point at which the disk is no longer detectable at IRAC wavelengths). As a result, IRAC 8 μm excess is arguably the best current method with which to reliably detect the presence of an inner circumstellar disk and study the effects of star-disk interaction on the angular momentum history of young stars.

In this paper, we present a new study of the angular momentum history of two young stellar clusters, the ONC ($\sim$1 Myr) and NGC 2264 ($\sim$2–3 Myr). In § 2, we discuss results from previous work on these two clusters and IC 348, the other well-studied PMS star cluster, detailing the important factors, such as accurate disk identification and sample selection, needed to isolate the effects of circumstellar disks on the current rotation period distributions of young clusters. In § 4, we describe our new results from NGC 2264, using rotation periods from the literature and public *Spitzer* data, and a reanalysis of the data in the ONC study presented by Rebull et al. (2006) using the same mass sample for each study, with a stricter sample selection in the ONC because of the different extinction levels in that cluster. In § 5, we compare the two results and discuss robust Monte Carlo simulations, already underway, which will determine what star and disk evolution parameters are allowed given the current rotation period distributions of stars with and without a disk in each cluster. Future work on the subject is also proposed. Our conclusions are summarized in § 6.

2. PREVIOUS OBSERVATIONAL RESULTS

Three clusters have been studied extensively to produce rotation periods from photometric monitoring campaigns, spectral types from spectroscopy and photometric colors, and disk identification from various disk indicators. Until *Spitzer* mid-IR data became available, disk identification was limited to ground-based color excesses, mostly in the NIR, and Hα equivalent widths.

These indicators, however, have not provided disk identification accurate and reliable enough to study the effect circumstellar disks have had throughout the lives of PMS stars at the age of these clusters. The correlation between rotation period and NIR color excess can be masked by biases introduced by these data. For instance, it has been shown that the NIR disk indicator misses 30% of the disks that can be detected at longer wavelengths (Hillenbrand et al. 1998). In addition, the ground-based photometry used to calculate the excess most often comes from different epochs, which can affect the results due to the high photometric variability of these stars (Rebull 2001).

Moreover, correlations between rotation period and NIR excess can be caused by a secondary effect of the correlation between mass and rotation period, in a sense mimicking the result expected from star-disk interaction (Littlefair et al. 2005). As shown by previous work (Herbst et al. 2000, 2002; Lamm et al. 2005; Paper I), rotation period distributions of PMS stars are highly dependent on mass. PMS stars of later spectral types behave differently from stars M2 and earlier, corresponding to masses of $M \geq 0.25\ M_{\odot}$ at the ages of these clusters, according to theoretical evolutionary tracks (D'Antona & Mazzitelli 1998); these are hereafter referred to as high-mass stars. ONC high-mass stars show a bimodal period distribution, while low-mass stars rotate more rapidly than the high-mass stars, with a unimodal distribution peaking at $\sim$2 days and a tail of longer periods (Herbst et al. 2001). In NGC 2264, the high-mass stars do not show a clear bimodal distribution, but they do rotate more slowly than the low-mass population. The low-mass period distribution is also more sharply peaked than the high-mass distribution. Due to the difference in the color contrast between the stellar photosphere and the inner disk, NIR excess tends to be greater for high-mass stars than for low-mass stars (Hillenbrand et al. 1998), and since lower mass stars tend to rotate faster than higher mass stars, this can result in a correlation between NIR excess and rotation period that is not necessarily connected to star-disk interaction. Therefore, these two different populations must be studied separately.

Spitzer's Infrared Array Camera (IRAC, 3.6–8.0 μm; Fazio et al. 2004) allows the first observations sensitive enough at mid-IR wavelengths to accurately determine the presence of inner circumstellar disks for a statistically significant number of PMS stars with known rotation periods. The observations at every IRAC wavelength are also observed concurrently, overcoming previous limitations caused by stellar magnitude variations between observations. However, even with an accurate identification of circumstellar disks, biases and selection effects can still mask useful measurements of the effects of star-disk interaction on young stellar populations. As discussed in §§ 3 and 4, selecting a uniform and complete sample of stars is critical in order to be able to detect the role star-disk interaction has in the angular momentum evolution of PMS stars. What follows is a more detailed discussion of the mixed results of previous searches for the effects of star-disk interaction on rotation period distributions in each cluster.

2.1. *NGC 2264*

Virtually all $\sim$500 known rotation periods in NGC 2264 can be collected from two studies (Makidon et al. 2004; Lamm et al. 2005). Makidon et al. (2004) conduct a study of 201 stars in this cluster. They examine the hypothesis that star-disk interaction regulates the angular momentum of PMS stars by searching for a correlation between rotation period and four different disk indicators ($U - V$, $I_C - K_s$, $H - K_s$, and Hα). They find "no conclusive evidence that more slowly rotating stars have disk indicators, or that faster rotating stars are less likely to have disk indicators." Lamm et al. (2005) investigate the disk regulation hypothesis in NGC 2264 by studying rotation period distributions of CTTSs and WTTSs using a $R_C - \mathrm{H}\alpha$ versus $R_C - I_C$ color criterion to distinguish between the two populations. They find that the distribution of rotation periods of the high-mass CTTS and WTTS populations "looks quite different" even though "the statistics are poor." Namely, according a Kolmogorov-Smirnov (K-S) test, they find that there is a 0.02 probability that the distributions of high-mass CTTSs and WTTSs are equivalent. They attribute this marginally significant difference in the rotation period distribution to the fact that the stars classified as CTTS are more likely to have a disk than those classified as WTTS. Although they attempt to separate stars by both mass and disk presence, their results are hampered by an inefficient disk identifier. Fewer than half of their high-mass stars, for example, are used in their analysis (72 of 184), leaving 112 stars as ambiguous disk identifications.

2.2. *Orion Nebula Cluster*

There are over 900 known rotation periods for the ONC, the focus of most studies of angular momentum evolution of PMS stars. Edwards et al. (1993) conduct a study of 34 T Tauri stars from Taurus and the ONC, ranging in spectral type from K7 to M1 and in age from 1 to 10 Myr. They show a correlation between $H - K$ excess and rotation period for these stars; however, in a subsequent study by Stassun et al. (1999) for stars in the ONC, no such correlation was found. Herbst et al. (2000) find a strong period dependence on stellar mass and confirm the bimodal distribution for high-mass stars originally suggested by an earlier study from that group (Attridge & Herbst 1992). They explain that the previous study by Stassun et al. (1999) did not exhibit the bimodal period distribution because its sample was dominated by low-mass stars. They find a "weak but significant" correlation with period among stars with $M > 0.25\,M_\odot$, but argue that the strongest evidence for disk locking is the bimodal distribution itself.

Rebull (2001) study four fields in the outer ONC, surrounding but not including the Trapezium region. They conclude that "There is no unambiguous correlation of period with $I_C - K_s$, $H - K_s$, and $U - V$ color excesses or more indirect disk indicators; the slowest rotators are not necessarily the disk candidates, and the disk candidates are not necessarily the slow rotators, regardless of how one defines a disk candidate" (Rebull 2001).

Subsequently, Herbst et al. (2002) show a correlation between rotation period and $I - K$ excess for stars in the ONC that they claim has a "very high" level of significance. They find that slower rotators with periods >6.28 days show a mean IR excess emission, $\Delta(I - K) = 0.55 \pm 0.05$, and more rapidly rotating stars with periods <3.14 days have a mean $\Delta(I - K)$ of 0.17 ± 0.05. With this result, they claim, "The long-suspected, but somewhat controversial, correlation between rotation and excess infrared emission, which is relevant to the disk-locking hypothesis, is finally confirmed at a very high significance level. There is no doubt now that more slowly rotating stars in the ONC have, on average, greater infrared excess emission than do their more rapidly rotating counterparts" (Herbst et al. 2002). This correlation between rotation and the magnitude of the excess infrared emission has been interpreted by the Herbst group as conclusive support of the star-disk interaction hypothesis (Herbst et al. 2002, 2007).

However, having failed to find a correlation between period and disk indicators such as Hα emission, $U - V$ color excess, and $K - L$ color excess, other groups have a different interpretation of the Herbst et al. (2002) results and argue that the observed correlation between period and magnitude of the infrared excess does not represent strong support for star-disk interaction. Makidon et al. (2004) state that neither the presence nor the magnitude of an NIR excess are necessarily well correlated with the presence of a disk; inclination angle and inner disk hole effects can account for the NIR trends, meaning "correlations between period and NIR excess strength are not necessarily particularly meaningful" (Makidon et al. 2004). Littlefair et al. (2005) express similar concerns about the Herbst et al. (2002) result, and add an additional one: a mass effect. They point out that in addition to effects caused by disk mass, inclination angle, structure, and inner disk hole size, the level of $I - K$ excess is also strongly dependent on stellar mass; high-mass stars possess a significantly stronger excess than do low-mass stars (Hillenbrand et al. 1998). Furthermore, low-mass stars inherently rotate more rapidly than high-mass stars, and these combined effects can therefore result in the apparent correlation between rotation period and NIR excess. They conclude that "The claims that the ONC offers strong support for disc locking should therefore be interpreted with caution" (Littlefair et al. 2005).

We note that the slow and fast rotators ($\omega < 1$ and >2 rad day^{-1}, corresponding to periods longer than 6.28 days and shorter than 3.14 days, respectively), for which the Herbst et al. (2002) study finds very different IR excess distributions, indeed have very different mass distributions. In their short-period sample, there are twice as many low-mass stars as high-mass stars (80 vs. 40), while in their long-period sample, there are only 34 low-mass stars versus 84 high-mass stars. Moreover, the mean IR excess emission for long-period stars in the ONC found by the Herbst et al. study [$\Delta(I - K) = 0.55$] is increased significantly by the eight stars (all high-mass) with the highest excesses in the group.

Recently, using *Spitzer* IRAC data as a more reliable disk indicator, Rebull et al. (2006) studied the angular momentum problem in the ONC central and surrounding regions using periods from the literature. Having been able to accurately determine which stars have disks and which do not, they were able to show a connection between stellar rotation and the presence of a circumstellar disk. In particular, they show that stars with periods shorter than 1.8 days are significantly less likely to have a disk that stars with periods longer than 1.8 days. However, they also find that "among the slower rotators (stars with periods >1.8 days), the period distributions for stars with and without disks ($[3.6] - [8] > 1$ and <1, where bracketed notation indicates IRAC colors) are statistically indistinguishable." Although suggestive, by itself this result does not lend conclusive support to the star-disk interaction scenario because the short-period objects that represent the correlation make up less than 20% of the entire population, leaving over 80% of the objects showing no correlation. In addition, this 1.8 day period cut is arbitrary, chosen in order to maximize the result rather than for a specific scientific reason. Other factors, such as an overabundance of close binaries among fast rotators, could also account for the low disk fraction in this population (Rebull et al. 2006; Paper I). As shown in §§ 3 and 4, even when using *Spitzer* colors as a disk indicator, a general correlation between disk fraction and rotation period can only be seen across the entire period range after the mass effects and sensitivity biases are removed from the sample.

TABLE 1

NGC 2264 Stars with Periods from the Literature and *Spitzer* Data

R.A. (J2000.0) (deg)	Decl. (J2000.0) (deg)	R_C (mag)	I_C (mag)	Period (days)	Ref.	$F_{3.6}$ (mJy)	$err_{3.6}$ (mJy)	$F_{4.5}$ (mJy)	$err_{4.5}$ (mJy)	$F_{5.8}$ (mJy)	$err_{5.8}$ (mJy)	$F_{8.0}$ (mJy)	$err_{8.0}$ (mJy)
99.94500..............	9.68167	13.26	12.69	3.84	2	1.06E+01	1.60E−01	6.29E+00	9.98E−02	4.65E+00	1.11E−01	2.56E+00	6.06E−02
99.95292..............	9.60983	15.69	14.49	4.01	2	4.62E+00	6.79E−02	3.03E+00	3.46E−02	1.88E+00	4.59E−02	1.16E+00	3.30E−02
99.96287..............	9.60922	17.16	15.84	1.36	1	2.15E+00	3.25E−02	1.40E+00	2.47E−02	1.45E+00	5.61E−02	5.89E−01	3.39E−02
99.96954..............	9.62714	19.37	17.49	2.14	1	6.69E−01	1.15E−02	5.21E−01	8.07E−03	0.00E+00	0.00E+00	2.62E−01	2.25E−02
99.97625..............	9.94092	17.55	15.70	0.58	2	2.45E+00	3.49E−02	1.84E+00	2.66E−02	0.00E+00	0.00E+00	7.91E−01	3.91E−02

Notes.—References are given for the periods and optical photometry. Table 1 is published in its entirety in the electronic edition of the *Astrophysical Journal*. A portion is shown here for guidance regarding its form and content.

References.—(1) Lamm et al. 2005; (2) Makidon et al. 2004.

2.3. *IC 348*

To date, only two groups have searched for a period-disk correlation in IC 348 (~3 Myr). Littlefair et al. (2005) study a sample of 50 periodic stars and search for a correlation between period and $K - L$ color excess (available for 30 stars) and Hα (available for 43 stars), but find no significant correlation.

Thanks to a very deep IRAC Guaranteed Time Observation (GTO) survey (1600 s exposures per pixel), IC 348 is the only cluster of the three discussed in this paper that currently has deep enough observations to reach the photospheric level of the entire sample of periodic stars at all four IRAC wavelengths. In Paper I, a study of IC 348 using these *Spitzer* data, we find a similar result to that reported by Rebull et al. (2006) in the ONC, although with a smaller level of significance given the size of our sample.

Namely, in a total sample of ~130 stars with rotation periods, we find a small subset of cluster members that rotate with periods shorter than ~2 days, showing a significantly lower disk fraction than the rest of the cluster population. We also find no statistically significant difference between the rotation period distribution of stars with and without disks at periods longer than ~2 days. We analyze the populations of stars with and without disks regardless of stellar mass and the populations of high-mass and low-mass stars independently. When the entire sample is considered, we find a bimodal distribution of periods for the stars with disks, which offers no support for star-disk interaction. However, after subdividing by mass the population of stars with and without a disk, there are too few stars in each mass bin for the disk and no-disk populations to make the analysis as a function of period statistically meaningful (see § 5.1).

3. THE DATA

3.1. *NGC 2264*

3.1.1. *NGC 2264 Rotation Periods*

Makidon et al. (2004) report rotation periods for 201 stars. Based on their false alarm probability levels, they divide their periods into two quality categories, 1 and 2. Lamm et al. (2005) report rotation periods for 405 stars. We combined the 114 "quality 1" rotation periods reported by Makidon et al. (2004) and the 405 rotation periods from Lamm et al. (2005). There were 74 stars in common between these two groups of 114 and 405 stars, which means that we have selected a total of 445 individual stellar rotation periods. We list the periods of these stars in Table 1, along with their coordinates and the R_C and I_C photometry reported by the two groups. We adopt the periods from the Lamm et al. (2005) study for the 74 stars common to both studies. Their work shows that ~95% of these 74 stellar rotation periods are identical to those of the "quality 1" periods reported by the Makidon group, highlighting the reliability of all of the periods listed in Table 1.

3.1.2. *NGC 2264 Spitzer Data*

NGC 2264 was observed with IRAC (Fazio et al. 2004) as part of the *Spitzer* GTO program "Disk Evolution in the Planet Formation Epoch" (PID = 37). The observations consist of four dithers and were conducted in the High Dynamic Range mode, which includes 0.4 s observations before 10.4 s exposures at each dither position. This mode allows photometry of both bright and faint stars at the same time. Each dither consists of 7×11 IRAC fields with 290″ offsets, resulting in a total mapped area of $\sim 33' \times 51'$ at each of the IRAC wavelengths (3.6, 4.5, 5.8, and 8.0 μm). See Young et al. (2006) for a more detailed description of the IRAC observations of NGC 2264. We retrieved from the *Spitzer* Science Center (SSC) archive the Basic Calibrated data of NGC 2264 that were processed with the SSC pipeline version S11.0.2. The Astronomical Observation Request (AOR) Keys of the data are 0003956480, 0003956992, 0003956736, and 0003957248. We mosaicked the IRAC data and produced point-source catalogs for each band using the pipeline developed as part of the *Spitzer* Legacy Project, "From Molecular Cores to Planet-forming Disks" (c2d). See Evans et al. (2006) for a detailed description of the c2d pipeline.

3.1.3. *NGC 2264 Sample Selection*

Obtaining an unbiased sample is critical in order to be able to study the connection between circumstellar disks and PMS star angular momentum evolution. Using *Spitzer* data in our study of IC 348 (Paper I), we show that ~40% of the circumstellar disks identified with 5.8 and/or 8.0 μm excesses in IC 348 show no clear excess at shorter wavelengths, indicating the necessity of 8.0 μm data for every star in the sample to prevent missing disks which cannot be detected at shorter wavelengths.

We searched our point-source catalogs for IRAC fluxes of the periodic stars in NGC 2264 listed in Table 1. We found 3.6 μm fluxes for all 445 of the objects, and data for 436, 371, and 229 stars at 4.5, 5.8, and 8.0 μm, respectively. The fact that both *Spitzer*'s sensitivity and photospheric fluxes decrease with increasing wavelength explains the smaller number of detections at 5.8 and 8.0 μm. Following Paper I, we use the $[3.6] - [8.0]$ colors for disk identification purposes ($[3.6] - [8.0] < 0.7$ represents a bare stellar photosphere, and $[3.6] - [8.0] > 0.7$ a star with a disk); therefore, in order to preserve the reliability of our disk identification, we restrict our analysis to the 229 stars with available 3.6 and 8.0 μm fluxes.

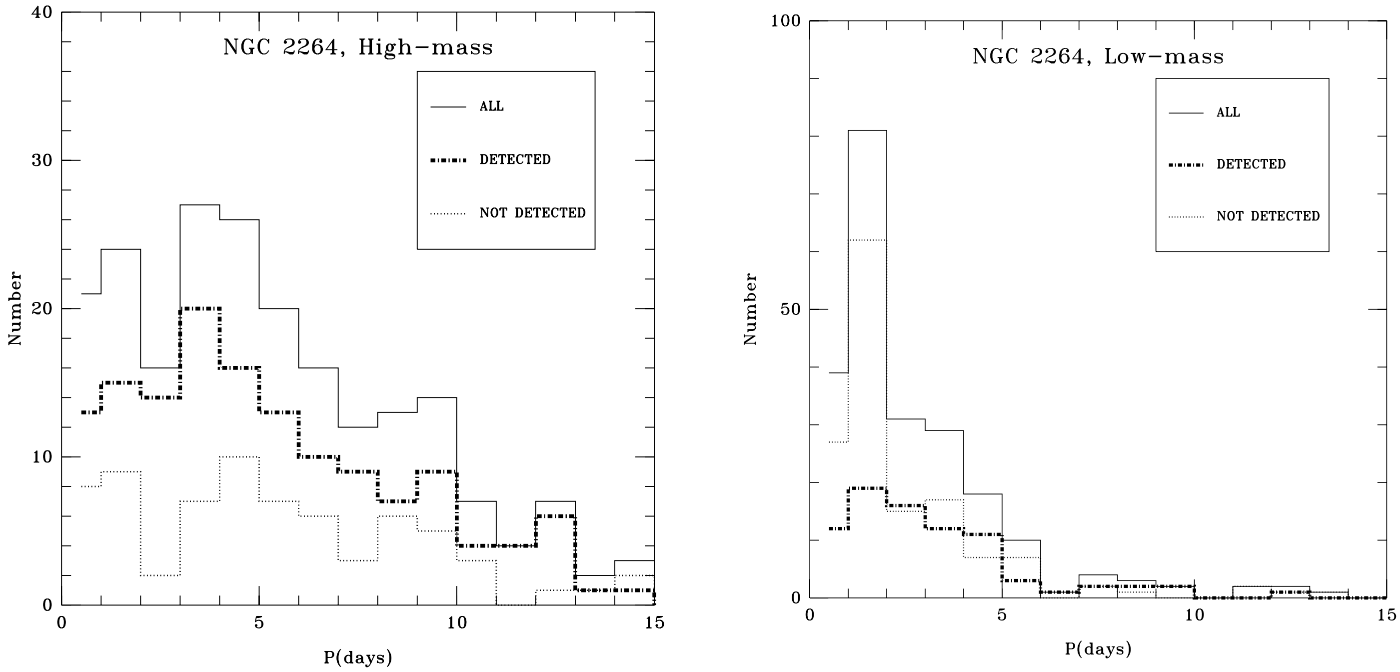

Fig. 1.—Mass-segregated period histograms for stars with and without 8.0 μm data in NGC 2264. *Left:* Period histogram for high-mass stars ($[R-I] < 1.3$) in NGC 2264. The three different lines represent all stars ($n = 212$, *solid line*), stars detected with *Spitzer*'s IRAC instrument at 8.0 μm ($n = 142$, *dot-dashed line*), and stars not detected at 8.0 μm ($n = 70$, *dotted line*). *Right:* Period histogram for low-mass stars ($[R-I] > 1.3$) in the cluster. The three different lines represent all stars ($n = 223$, *solid line*), stars detected with *Spitzer*'s IRAC instrument at 8.0 μm ($n = 81$, *dot-dashed line*), and stars not detected at 8.0 μm ($n = 142$, *dotted line*). As previously noted by Lamm et al. (2005) in NGC 2264 and Herbst et al. (2002) in the core of the ONC, low- and high-mass stars have clearly different period distributions. Since the 8.0 μm data are needed for a reliable disk identification (Rebull et al. 2006; Paper I), our analysis is restricted to stars detected at this wavelength. The period distribution of the high-mass stars detected at 8.0 μm is statistically indistinguishable from that of the undetected stars ($P = 0.96$, K-S two-sample test, $n_1 = 142$, $n_2 = 70$). In contrast, the period distribution of low-mass stars detected at 8.0 μm is significantly different from that of the undetected stars ($P = 1.6 \times 10^{-3}$, K-S two-sample test, $n_1 = 81$, $n_2 = 142$). As the low-mass sample has a much lower detected fraction of stars at shorter periods than at longer periods, the biases in this sample prevent us from using it.

3.1.4. *Mass Bias*

Because IRAC 8.0 μm data are required for reliable disk identification, a mass bias can be introduced due to the sensitivity limits of those data in a magnitude-limited sample. To illustrate this effect, in Figure 1 we plot histograms of the period distributions of the high- and low-mass stars in the NGC 2264 data set that were detected at 8.0 μm and those that were not. In the left panel, the period distribution of the high-mass stars detected at 8.0 μm is statistically indistinguishable from the distribution of stars with no 8.0 μm detection ($P = 0.96$, K-S two-sample test, $n_1 = 142$, $n_2 = 70$). In the right panel, on the other hand, the period distribution of low-mass stars detected at 8.0 μm is significantly different from that of the undetected stars ($P = 1.6 \times 10^{-3}$, K-S two-sample test, $n_1 = 81$, $n_2 = 142$). The fraction of stars with periods <2 days detected at 8.0 μm is 26%, and the fraction with $P > 2$ days detected is 46%. In the low-mass sample, there is a strong bias against the fastest rotators, which is expected if these stars are faint because they are the lowest mass stars in the sample and/or they preferentially have no disks. In addition, if optical colors are used to estimate mass, the low-mass sample can be contaminated by highly extincted high-mass stars, which have a different rotation period distribution from that of lower mass stars.

Since low-mass stars suffer from these two effects that render the current sample unreliable, we must segregate the sample by spectral type (corresponding to masses given by evolutionary tracks). Since brighter high-mass stars do not suffer as much from these sources of sample bias and contamination (reddened low-mass stars cannot be mistaken for high-mass stars), in addition to requiring *Spitzer* 8.0 μm detection, we further restrict our study to the high-mass population.

Spectral types to estimate masses are available for only a fraction of the stars in NGC 2264. However, NGC 2264 has relatively low extinction ($A_V \sim 0.5$ mag; Rebull 2001), which is fairly uniform across the field of view covered by this study. This allows us to use $R - I$ colors to make a mass cut and retain a relatively uncontaminated sample of high-mass stars. We use an $R - I$ color of <1.3 (corresponding to unextincted M2 stars and stars with earlier spectral types; Kenyon & Hartmann 1995) as the cutoff for this sample. Restricting our sample, as discussed, based on *Spitzer* data and stellar mass, leaves a final sample of 142 high-mass stars with known rotation periods detected by IRAC at 8.0 μm with which we search for a correlation between rotation period and the presence of a circumstellar disk.

3.2. *The Orion Nebula Cluster*

For our analysis of the ONC and its surroundings, we combine in Table 2 the rotation periods and *Spitzer* data presented by Rebull et al. (2006) with spectral types from the literature (Rebull 2001; Hillenbrand 1997). The study by Rebull et al. (2006) covers the intersection of the IRAC maps of the Orion star-forming complex (total area $\sim$6.8 deg^2) and the Orion regions containing stars with known rotation periods. These regions are the ONC (i.e., the region within the $\sim$20′ of the Trapezium) and the "flanking fields" (four $45' \times 45'$ fields centered $\sim$30′ east, west, north, and south of the ONC). The study of the ONC by Hillenbrand (1997) provides spectral types for $\sim$70% of the periodic stars studied by Rebull et al. (2006) that are located within their$34' \times 36'$ ONC field. Rebull (2001) provides spectral types for only $\sim$30% of the periodic stars studied by Rebull et al. (2006) that are located in the flanking fields.

TABLE 2
Orion Stars Detected in 3.6 and 8.0 μm with Periods from the Literature

Name[1]	R.A. (J2000.0)	Decl. (J2000.0)	$F_{3.6}$ (mag)	$\mathrm{err}_{3.6}$ (mag)	$F_{4.5}$ (mag)	$\mathrm{err}_{4.5}$ (mag)	$F_{5.8}$ (mag)	$\mathrm{err}_{5.8}$ (mag)	$F_{8.0}$ (mag)	$\mathrm{err}_{8.0}$ (mag)	Period (days)	Spectral Type	Ref.[2]	Mass[3]
R01 678	05 33 36.9	−05 23 06.2	11.52	0.006	11.52	0.008	11.47	0.027	11.44	0.119	7.23	...	...	NO
R01 680	05 33 37.1	−05 23 07.0	11.52	0.006	11.52	0.008	11.47	0.027	11.44	0.119	7.20	...	...	NO
R01 716	05 33 41.6	−04 55 59.9	11.91	0.006	11.90	0.009	11.78	0.018	11.88	0.027	7.55	M5.5	R01	L
R01 739	05 33 43.3	−06 05 23.5	12.09	0.007	12.16	0.012	12.04	0.019	11.97	0.024	3.99	M3.5	R01	L
R01 749	05 33 44.5	−06 05 20.5	12.39	0.009	12.36	0.011	12.36	0.020	12.36	0.031	15.42	...	...	NO
HBC 107.........	05 33 44.9	−05 31 08.6	9.92	0.002	9.97	0.003	9.89	0.007	9.82	0.039	2.64	...	...	NO
Par 1266..........	05 33 46.1	−05 34 26.5	10.84	0.003	10.84	0.004	10.84	0.011	10.90	0.039	4.65	K8	R01	H

Notes.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds. With the exception of the last three columns, all data come from Rebull et al. (2006). Table 2 is published in its entirety in the electronic edition of the *Astrophysical Journal*. A portion is shown here for guidance regarding its form and content.

[1] R01, Rebull (2001); HBC, Herbig & Bell (1988); Par, Parenago (1954); CHS, Carpenter et al. (2001); H97, Hillenbrand (1997); HBJM, Herbst et al. (2001); JW, Jones & Walker (1988).

[2] Reference for spectral type: R01, Rebull (2001); H97, Hillenbrand (1997).

[3] Stars with M2 and earlier spectral types are considered high-mass stars, while stars with M2.5 and later spectral types are considered low-mass stars.

3.2.1. *Orion Nebula Cluster Sample Selection*

A large fraction of the stars in the Rebull et al. (2006) sample do not have measured spectral types. For stars with no spectral type measurement, Rebull et al. (2006) make a mass cut by placing these stars on I versus $(V - I)$ color-magnitude diagrams. Unlike in the case of NGC 2264, this method is unreliable for the ONC sample because the extinction is high and highly variable ($A_V \sim 1$–5) across the entire field of view covered by the study (Hillenbrand 1997). Using colors for spectral type classification can lead to a blending of the period distribution of the high- and low-mass stars (see § 5.1 for a more detailed discussion). We therefore limit our analysis of the Rebull et al. (2006) sample of stars with known rotation periods to those with measured spectral types (M2 and earlier). This leaves 133 high-mass stars with which to monitor the effects of star-disk interaction.

4. RESULTS

4.1. *NGC 2264*

When disk fraction is plotted as a function of period for all NGC 2264 members without separating the populations by spectral type (Fig. 2, *left*), we find that the only significant feature is a lower disk fraction (17% ± 4%) for stars in the shortest period bin ($P \leq 2$ days) compared to that of the rest of the sample (45% ± 4%). For periods longer than 2 days, the distributions of periods for stars with and without a disk (Fig. 2, *right*) are statistically indistinguishable ($P = 0.211$, K-S two-sample test, $n_1 = 76$, $n_2 = 88$). This is, in essence, an identical result to those found in the *Spitzer* studies of the ONC (Rebull et al. 2006) and IC 348 (Paper I).

Using an $R - I$ color of <1.3 (corresponding to unextincted M2 stars and stars with earlier spectral types; Kenyon & Hartmann

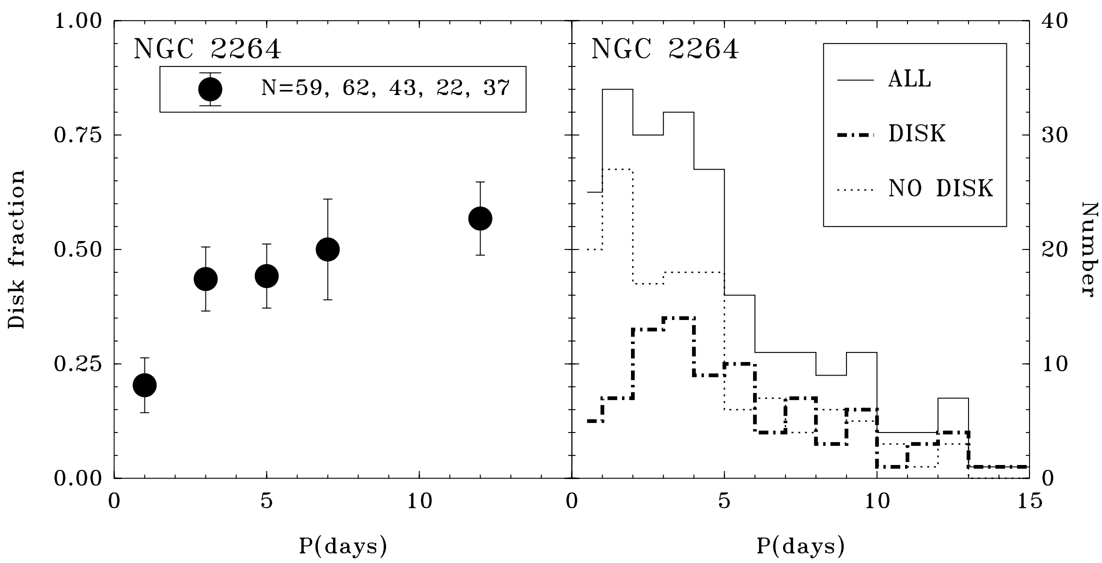

Fig. 2.—Results for all stars in NGC 2264. *Left:* Disk fraction as a function of period for the stars in NGC 2264 with rotation periods <15 days and both 3.6 and 8.0 μm IRAC data, enough for an accurate disk identification. The error bars represent the 68% confidence level (1 σ) of the measurements. The only significant feature is the lower disk fraction of the stars with shortest periods ($P < 2$ days) with respect to that of the rest of the sample. *Right:* Period histogram for the same sample of stars. The three different lines represent all stars (*solid line*), stars with IR excess indicating the presence of a disk (*dot-dashed line*), and stars with no detected disk signature (*dotted line*). For periods longer than 2 days, the distribution of periods for stars with and without a disk are statistically indistinguishable ($P = 0.211$, K-S two-sample test, $n_1 = 76$, $n_2 = 88$).

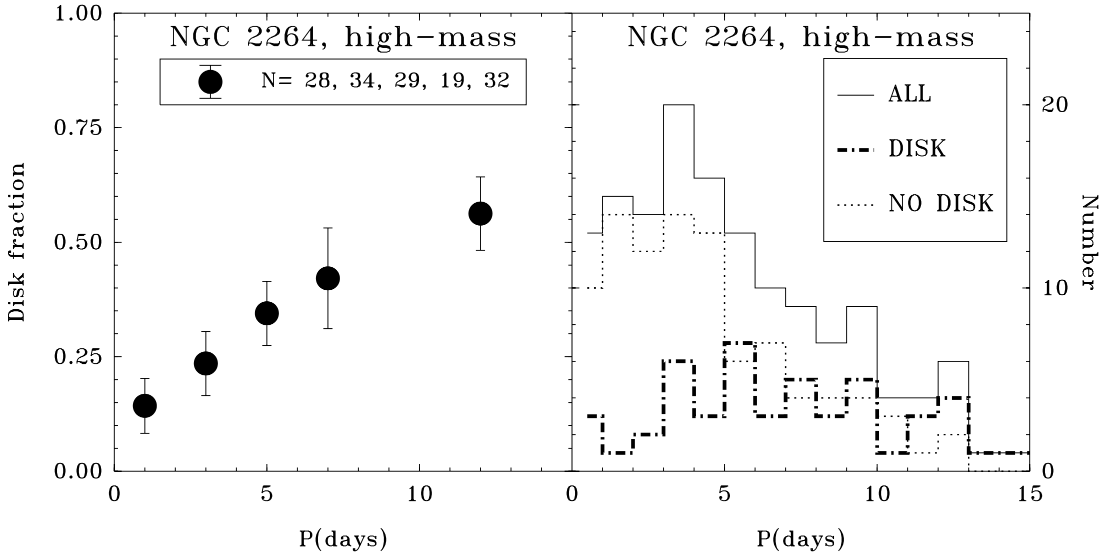

FIG. 3.—Results for high-mass stars in NGC 2264. *Left:* Disk fraction as a function of period for high-mass stars. The error bars represent the 68% confidence level (1 σ) of the measurements. When only high-mass stars are considered, the connection between the presence of a disk and slow rotation becomes evident across the entire range of the period distribution. *Right:* Period histogram for high-mass stars. The three different lines represent all the stars (*solid line*) and stars with and without a disk (*dot-dashed line and dotted line, respectively*). The period distribution of diskless high-mass stars peaks at short periods ($P < 5$ days), while the periods of high-mass stars with disks are consistent with a flat distribution. These distributions are significantly different ($P = 6.1 \times 10^{-5}$, K-S two-sample test, $n_1 = 48$, $n_2 = 94$). This result suggests that stars without disks are free to spin up faster than stars with disks.

1995) as the cutoff for high-mass stars and plotting disk fraction as a function of period for the high-mass sample in NGC 2264 (Fig. 3, *left*), a clear increase in the disk fraction with period is revealed across the entire period range covered by the sample. *Spitzer*'s 8.0 μm IRAC band is the first source of data to provide unambiguous disk identification, allowing the populations of stars with and without disks to be separated and plotted individually. A histogram of the period distributions for high-mass stars with and without a disk (Fig. 3, *right*) shows that these distributions are significantly different ($P = 6.1 \times 10^{-5}$, K-S two-sample test, $n_1 = 48, n_2 = 94$). Although there is a relatively flat distribution of stars with disks, there is a large peak of shorter period stars (1–5 days) with no disks and far fewer with long periods. These different distributions are a clear indication that star-disk interaction regulates the angular momentum of stars as they contract onto the main sequence.

4.2. *The Orion Nebula Cluster*

The evidence for angular momentum regulation through star-disk interaction is equally dramatic in Orion if one restricts the sample studied by Rebull et al. (2006) by spectral types in the literature (Hillenbrand 1997; Rebull 2001) to stars of spectral type M2 and earlier, even though the sample of stars with rotation periods is cut in half as a result. If disk fraction is plotted as a function of period for the restricted sample (Fig. 4, *left*), a clear increase in the disk fraction with period is revealed across the entire period range populated by the Orion stars. A histogram of the period distributions for high-mass stars with and without a disk (Fig. 4, *right*) shows that these distributions are dramatically different ($P = 9.99 \times 10^{-7}$, K-S two-sample test, $n_1 = 58$, $n_2 = 75$).

Based on the star-disk interaction paradigm, Herbst et al. (2000) predict that the long-period peak ($P \sim 8$ days) seen in the clear bimodal period distribution of the high-mass stars in the ONC should be dominated by stars with disks, while the short-period peak ($P \sim 2$ days) should be dominated by stars without disks. Rebull (2001) includes stars in the ONC and in surrounding regions (the "flanking fields"), which are composed of older stars than those in the younger central region of the cluster and do not show such a clear bimodal distribution as the ONC. If one further restricts their sample to stars in the ONC (84.1° > R.A. > 83.0°, 5.0° > decl. > −5.7°) with measured spectral types (Fig. 5, *left*), one recovers the bimodal distribution seen by earlier observations (Attridge & Herbst 1992; Herbst et al. 2000, 2002). A period histogram of stars with disks overplotted on a period histogram of stars without disks (Fig. 5, *right*) reveals two distinct and cohesive rotation period distributions, one populated by stars lacking disks peaked at $P \sim 2$ days and the other by stars with disks peaked at $P \sim 8$ days, which, blended together, form the bimodal distribution of the high-mass stars in the ONC. Separating and plotting individually these two populations of stars with and without disks results in an unambiguous indication that star-disk interaction has prevented the spin-up of PMS stars in the ONC.

5. DISCUSSION

5.1. *The Mass Effect*

In § 4, we have discussed the significant differences in the period distributions of low- and high-mass stars in NGC 2264 and the ONC. These differences are not fully understood but can be partially accounted for by the fact that lower mass stars of a given age have smaller radius, R. Thus, for a given specific angular momentum, j ($j \propto R^2/P$), they are in fact expected to have a shorter period, P (Herbst et al. 2001). However, since j still seems to be higher for low-mass stars than for the high-mass counterparts, it has also been suggested that the disk regulation mechanism is less efficient in low-mass stars than in high-mass stars due to differences in accretion rates and the strength or structure of their magnetic fields (Lamm et al. 2005).

It is easy to show, by making a slightly different mass cut in our ONC analysis, that even small inaccuracies in spectral classification can lead to a severe blending of the period distributions of stars with and without disks. In Figure 6, we compare the mass cut we use in our analysis (*left*) to a slightly different

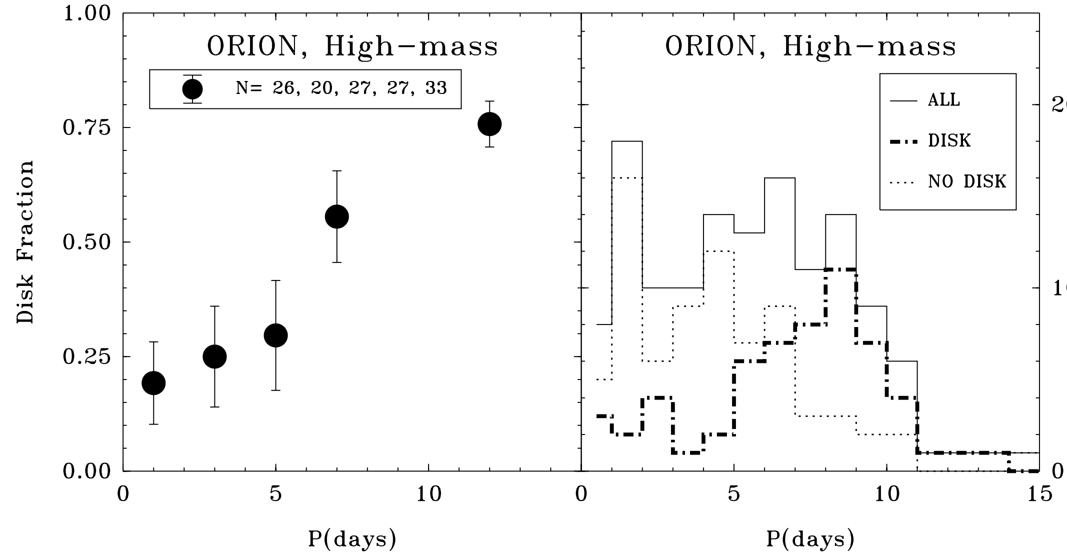

Fig. 4.—Results for high-mass stars in Orion. *Left:* disk fraction as a function of period for high-mass stars with measured spectral types in the ONC and surrounding flanking fields. The error bars represent the 68% confidence level (1 σ) of the measurements. As with NGC 2264, the disk fraction clearly increases with period across the entire period range covered by the data. *Right:* Period histograms for high-mass stars. The three different lines represent all the stars (*solid line*) and stars with and without a disk (*dot-dashed line and dotted line, respectively*). The overall distribution is clearly a blend of the two distinct period distributions, which are significantly different from each other ($P = 9.99 \times 10^{-7}$, K-S two-sample test, $n_1 = 58$, $n_2 = 75$). The distribution of stars possessing a circumstellar disk is centered at a period much longer than the distribution of stars with no disk. Once again, the results from the high-mass stars in the ONC and surrounding regions clearly suggest that circumstellar disks are involved with angular momentum regulation in these young stars.

mass cut, including lower mass stars by one spectral subtype in the sample (*right*). Because low-mass stars inherently rotate faster than high-mass stars, regardless of the presence of a disk, contaminating the high-mass sample with low-mass stars will mask the effect that star-disk interaction has on PMS star rotation periods.

The extreme sensitivity of period distribution to mass is difficult to explain in terms of slowly varying quantities such as radius and accretion rates. The observed dependence of rotation periods on mass is most consistent with the picture that a *sudden* change in the strength or structure of the magnetic field at the boundary between M2 and M3 stars is responsible for the observed differences in period distributions of low-mass and high-mass PMS stars. We note that, depending on the evolutionary tracks used, the masses corresponding to given spectral types will change. Siess et al. (2000) tracks, for example, give slightly higher masses than do those of D'Antona & Mazzitelli (1998). However, the boundary we draw between the high- and low-mass samples

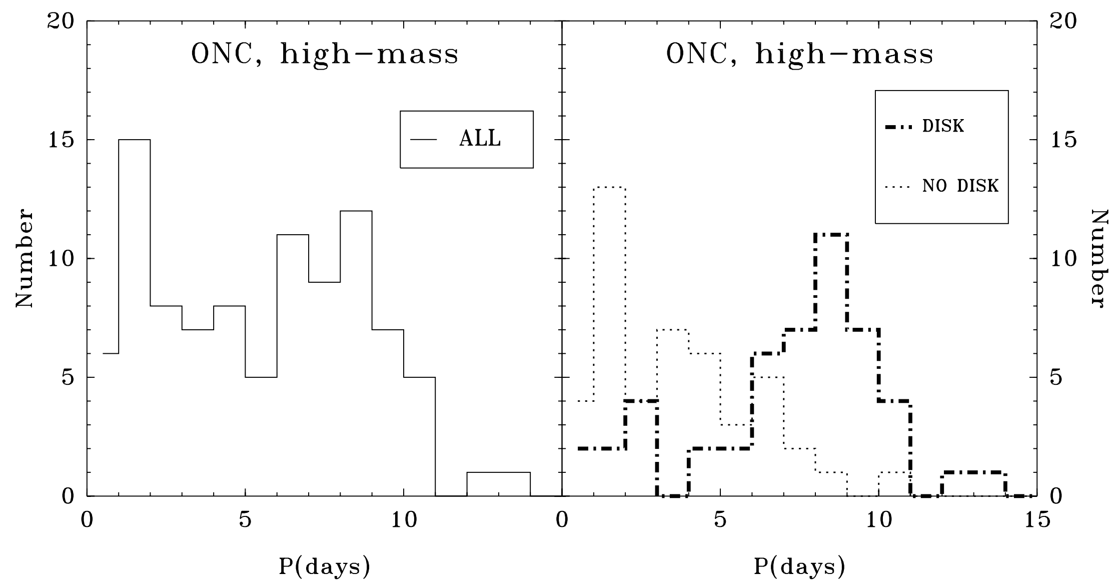

Fig. 5.—Results for high-mass stars in the central regions of the ONC. *Left:* Period histogram of all high-mass stars in the central region of the ONC that have measured spectral types. *Right:* Period histograms for the same stars with (*dot-dashed line*) and without (*dotted line*) a disk. When restricting the sample by not including the flanking fields, the bimodal period distribution seen by previous studies (Attridge & Herbst 1992; Herbst et al. 2002) is recovered. With an accurate disk identifier and sample selection based on spectral types, one can see that the bimodal distribution is a blend of two dramatically different distributions, stars with and without protoplanetary disks ($P = 4.3 \times 10^{-8}$, K-S two-sample test, $n_1 = 49$, $n_2 = 46$). The diskless, high-mass population is centered at a much shorter period than the population with disks, again unambiguously supporting the picture of angular momentum regulation through star-disk interaction.

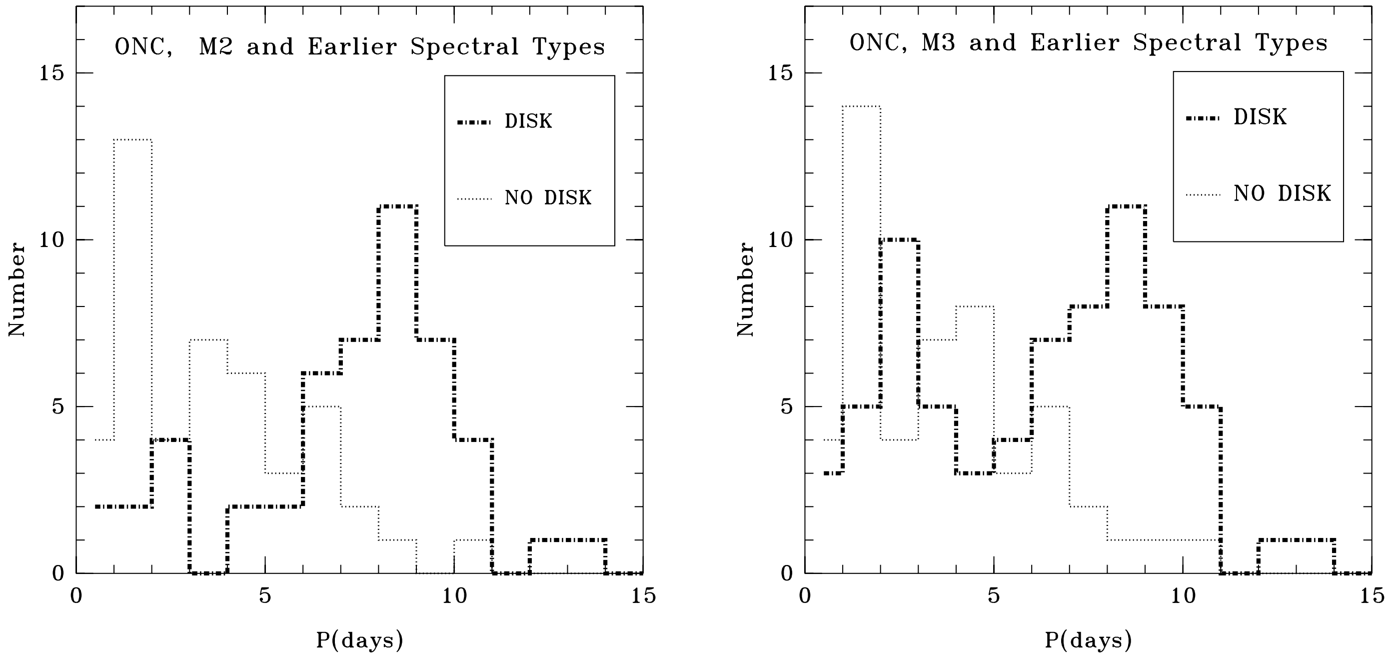

Fig. 6.—Effect of a different mass cut on the period distribution of stars with and without disks in the ONC. *Left:* Period histogram for high-mass stars (M2 and earlier spectral types) with ($n = 49$) and without ($n = 46$) a disk (*dot-dashed line and dotted line, respectively*). *Right:* Same plot with a slightly different mass cut. This histogram includes M3 stars (i.e., stars with slightly lower masses). Again, stars with disks ($n = 71$) are represented by a dot-dashed line and stars without disks ($n = 50$) by a dotted line. This panel shows that even a *small* contamination of the high-mass star sample by stars with slightly lower masses will result in a short-period ($P < 4$ days) peak of stars with disks that will weaken the observational signature of star-disk interaction on angular momentum (P increases from 4.3×10^{-8} to 1.1×10^{-4} in a K-S two-sample test when comparing the disk and no-disk samples in the right panel to those in the left). This is because low-mass stars (M3 and later spectral types) tend to have very short periods ($P < 4$ days) regardless of the presence of a disk.

is based on spectral type, and our conclusions are not affected by the difference in the corresponding masses derived from different evolutionary tracks.

The vast majority of stars of the masses and ages of those considered in our study are fully convective. Unfortunately, the dynamos operating in fully convective stars are far less understood than the solar-type dynamo, which operates in the boundary layer between the convective envelope and the radiative core. Models disagree on the magnetic field strengths and topologies that can arise from fully convective stars (Brun et al. 2005; Chabrier & Küker 2006) and are clearly not advanced enough to predict how the strengths and topologies depend on stellar mass (Donati et al. 2006). The extreme sensitivity of period distribution to stellar mass could represent an important observational constraint for the theoretical work in the area.

The extreme sensitivity of period distribution to mass also explains previous *Spitzer* results that showed inconclusive evidence of the star-disk interaction scenario. Rebull et al. (2006) found a separate subpopulation of fast rotators with $P \leq 2$ days with a low disk fraction (where there are few high- or low-mass stars with disks) and statistically indistinguishable period distributions for stars with and without disks at $P > 2$ days (as is the case with NGC 2264 when analyzing the entire sample instead of only high-mass stars). The longer period stars in those results are a blend of high- and low-mass stars which have different period distributions, affected by something other than star-disk interaction alone.

In Paper I, we obtained the same result for IC 348 because that cluster has too few member stars with known rotation periods to study the high- and low-mass samples separately (Fig. 7). As a result, after isolating the small sample, we find only a 1 σ hint that the high-mass stars rotating slower than the median ($P = 6.2$ days) have a higher disk fraction (50% $\pm$ 10% [12/24]) than the

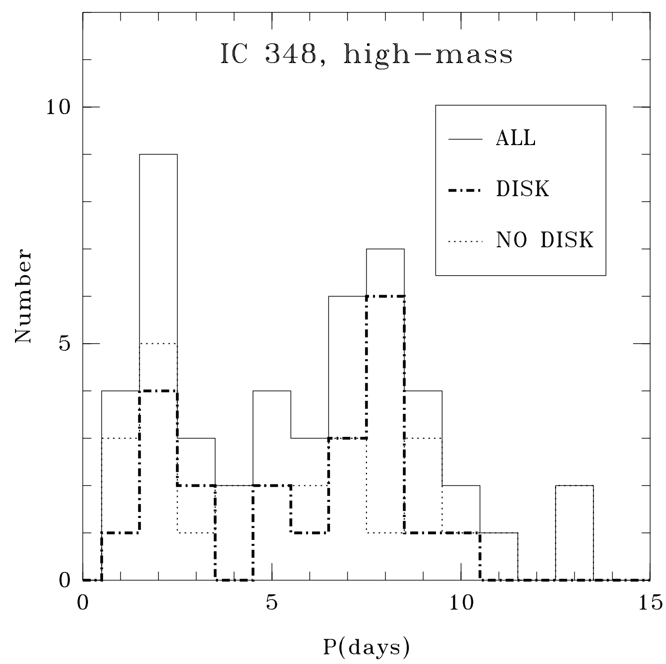

Fig. 7.—Histograms of high-mass stars in IC 348. After dividing the IC 348 sample of stars with known rotation periods by mass, there are too few stars to study the disk and no-disk populations separately. As seen in the figure, very few (or no) stars remain in each period bin. More rotation periods in that cluster would be needed to observe signatures of star-disk interaction affecting the period distributions.

high-mass stars rotating faster than the median (39% ± 10% [9/23]). We predict that once a significant number of rotation periods (100–150) become available for high-mass stars in IC 348 and its surroundings, the same clear increase in disk fraction with rotation period seen in NGC 2264 (Fig. 3) and the ONC (Figs. 4 and 5) will become evident in the IC 348 region as well.

5.2. *Outstanding Questions*

5.2.1. *Quantitative Models*

Our results from § 4 show that by restricting the sample of PMS stars studied to those with an accurately determined mass range, and by using a reliable disk indicator such as the photometry from *Spitzer*'s IRAC instrument, clear observational signatures of star-disk interaction become evident. Using *Spitzer* mid-IR data as a disk indicator, we can finally progress from first-order issues such as whether or not circumstellar disks regulate the angular momentum evolution of PMS stars to ones such as what initial conditions and PMS star and disk parameters are consistent with the observed period distributions of stars with and without a disk, or what constraints the observed distributions can place on disk evolution.

For instance, comparing the observed period distributions to Monte Carlo simulations (introduced by Rebull et al. [2004] and improved on in the discussion in Paper I) can give us information about the disk-release time of PMS stars and the efficiency with which the disks drain their angular momentum. Results from Rebull et al. (2004) suggested that a significant fraction (~30%) of high-mass stars must evolve conserving angular momentum from the time they form in order to reproduce the bimodal distribution observed in the ONC. In the context of star-disk interaction, this implies an extremely short disk lifetime (<1 Myr) for a significant number of stars. Preliminary comparisons of the period distributions of stars with and without a disk presented herein against much more detailed Monte Carlo models (Cieza et al. 2006) confirm the Rebull et al. (2004) result. Short disk lifetimes are also detected independently in the results of recent *Spitzer* surveys (Padgett et al. 2006; Cieza et al. 2007) that find that up to 50% of the youngest WTTSs (age $\lesssim$ 1 Myr) show photospheric emission in the mid-IR (8.0–24.0 μm). Our Monte Carlo models show that the period distribution of the stars lacking disks is very sensitive to short disk dissipation timescales because the effects of star-disk interaction are more important at early ages when the stars undergo very rapid contraction.

The sensitivity of current PMS star rotation period distributions to short disk dissipation timescales allows this type of numerical analysis to put valuable constraints on both disk dissipation and planet formation timescales and, hence, possibly formation mechanisms. A detailed comparison of the observed period distributions of NGC 2264 and the ONC presented herein to Monte Carlo models will be presented in a follow-up paper.

5.2.2. *Cluster to Cluster Comparisons*

The high-mass stars in the two clusters studied in this work, the ONC and NGC 2264, have substantially different rotation period distributions. In particular, NGC 2264 lacks the long period peak at ~8 days, and its stars with disks show a much flatter distribution than do those in the ONC. Lamm et al. (2005) argue that NGC 2264 is twice as old as the ONC and represents a later stage in rotational evolution. By assuming that at the age of the ONC, NGC 2264 had the exact period distribution as the ONC has today, they estimate that ~80% of the stars in NGC 2264 have spun up from the time it was the age of the present-day ONC until now, while only ~30% have remained locked to their disks.

However, the difference in rotation period distributions is also likely constrained by initial conditions and formation environment. Characteristics such as stellar density, cluster initial mass function, and overall cluster mass might play a role in the angular momentum evolution of PMS stars. The kind of numerical models described above can be used to test whether the period distributions observed in the ONC will naturally evolve into the period distributions observed in NGC 2264 or if different initial conditions and model parameters are required to reproduced the observed period distribution of each cluster.

The observations of NGC 2264 and the ONC studied here only represent a small fraction of the *Spitzer* data capable of playing a role in disentangling the steps in the evolution of PMS stars and their disks. *Spitzer* data currently exist for tens of young nearby clusters awaiting photometric monitoring campaigns to obtain rotation periods. Further studies of other clusters of different ages (from less than 1 to more than 10 Myr) will provide a broader age baseline with which to study the evolution of angular momentum of PMS stars, while the study of clusters of different sizes will establish the importance of PMS stellar environment on this evolution.

5.2.3. *Low-Mass Population*

The only current complete sample of stars with rotation periods in either of the well-studied clusters focused on in this work is the high-mass sample, or stars of spectral type M2 and earlier. Although these stars provide a very clear signature that star-disk interaction is regulating the spin-up of PMS stars as they contract onto the main sequence, the whole story is yet untold. Lower mass stars, half of all stars with known rotation periods, cannot currently be studied to see if their rotation periods are similarly affected by their circumstellar disks as no cluster has *Spitzer* data deep enough to provide an unbiased sample of low-mass stars. It is clear that the rotation period behavior of these stars is very different from that of their high-mass counterparts, but the reason for this difference is still unknown. These stars might have a lower overall disk fraction than high-mass stars, which would explain the more rapid rotation of these objects. However, if their were no difference in the disk fraction of these stars, then something internal to the star itself, resulting in a different magnetic field structure for these objects, could prevent star-disk interaction from regulating their angular momentum in the same way it does for high-mass stars.

The only cluster currently suited to being studied in this way is NGC 2264, both because it is a rich cluster with many member stars with known rotation period and because it has a low enough background brightness to allow deep *Spitzer* observations to detect bare stellar photospheres for the entire periodic sample.

6. CONCLUSIONS

We combined stellar rotation periods of the young cluster NGC 2264 from the literature with *Spitzer* photometry in order to search for the correlation between slow stellar rotation and mid-infrared excess predicted by disk regulation through star-disk interaction. We also reanalyzed results from the recent Rebull et al. (2006) study of the ONC using criteria similar to those used in the NGC 2264 analysis. These two clusters combined contain the vast majority of all known rotation periods of PMS stars. Thanks to the unprecedented disk detection capabilities of *Spitzer*, our results provide the strongest observational evidence to date that star-disk interaction regulates PMS star angular momentum. Our main conclusions can be summarized as follows.

1. When stars of all masses in NGC 2264 are considered together, the only significant result is the lower disk fraction of objects with short periods ($P \leq 2$ days), a range that contains only ~20% of the periodic stars, with respect to that of the rest of the sample. This is the same result found by Rebull et al. (2006) for the ONC and by itself provides only ambiguous support for the disk regulation paradigm. However, we show that the apparent lack of a clear overall correlation between period and IR excess across the entire period range is due to the strong dependence of rotation period on stellar mass and a sensitivity bias against low-mass stars lacking disks.
2. When only the high-mass stars ($R - I < 1.3$) in our NGC 2264 sample are considered, the correlation between stellar rotation and IR excess becomes evident across the entire period range of the sample.
3. The NGC 2264 periodic sample of low-mass stars ($R - I > 1.3$) with 8.0 μm data (used for disk identification) is highly biased against the fastest rotators. The bias in the low-mass star sample can be explained if the fastest rotators are the lowest mass stars in the sample and/or preferentially have no disk. This bias, which masks disk regulation signatures, does not exist in the high-mass star sample.
4. When the periodic sample of ONC stars presented by Rebull et al. (2006) is restricted to high-mass stars with reliable mass estimates, the correlation between stellar rotation and mid-IR excess becomes apparent across the entire range of the period distribution in the ONC sample as well.
5. We show that the long-period peak ($P \sim 8$ days) of the bimodal distribution observed for high-mass stars in the ONC is dominated by a population of stars with disks, while the short-period peak ($P \sim 2$ days) is dominated by a population of stars without a disk. This result confirms one of the main predictions of the star-disk interaction scenario (Herbst et al. 2000).
6. We argue that a quantitative comparison between the period distribution of stars with and without a disk to numerical models is needed to constrain disk regulation parameters such as the angular momentum transfer efficiency, fraction of regulated stars as a function of time, etc. We will present such a quantitative comparison to Monte Carlo models in a follow-up paper.
7. The current samples of periodic high-mass stars in NGC 2264 and the ONC with reliable disk indicators (e.g., [3.6]−[8.0] colors) are fairly large and unbiased. However, accurate mass indicators (i.e., spectral types) and deeper *Spitzer* observations are still needed for an unbiased quantitative study of the role that star-disk interaction plays in the evolution of low-mass stars.
8. Photometric monitoring of the many other young clusters already observed by *Spitzer* will reveal the importance of age and stellar formation environments in the angular momentum evolution of PMS stars.

Support for this work, part of the *Spitzer* Legacy Science Program, was provided by NASA through contract 1224608 issued by the Jet Propulsion Laboratory, California Institute of Technology, under NASA contract 1407.

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