

## THE MASS DEPENDENCE OF STELLAR ROTATION IN THE ORION NEBULA CLUSTER

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Received 2001 March 30; accepted 2001 May 14; published 2001 June 8

### ABSTRACT

We have determined new rotation periods for 404 stars in the Orion Nebula cluster (ONC) using the Wide Field Imager attached to the MPG/ESO 2.2 m telescope on La Silla, Chile. Mass estimates are available for 335 of these, and most have  $M < 0.3 M_{\odot}$ . We confirm the existence of a bimodal period distribution for the higher mass stars in our sample and show that the median rotation rate decreases with increasing mass for stars in the range  $0.1 M_{\odot} < M < 0.4 M_{\odot}$ . While the spread in angular momentum  $J$  at any given mass is more than a factor of 10, the majority of lower mass stars in the ONC rotate at rates approaching 30% of their critical breakup velocity, as opposed to 5%–10% for solar-like stars. This is a consequence of *both* a small increase in observed specific angular momentum ( $j = J/M$ ) and a larger decrease in the critical value of  $j$  with decreasing mass. Perhaps the most striking fact, however, is that  $j$  varies by so little—less than a factor of 2—over the interval  $0.1$ – $1.0 M_{\odot}$ . The distribution of rotation rates with mass in the ONC (with an age of  $\sim 1$  Myr) is similar in nature to what is found in the Pleiades (with an age of  $\sim 100$  Myr). These observations provide a significant new guide and test for models of stellar angular momentum evolution during the protostellar and pre-main-sequence phases.

*Subject headings:* open clusters and associations: individual (Orion Nebula Cluster) — stars: pre-main-sequence — stars: rotation

### 1. INTRODUCTION

Rotation is an undoubtedly important but often neglected aspect of stellar evolution. Our knowledge of the angular momentum evolution of stars, in particular, how it depends on mass, is seriously incomplete, especially for low-mass stars. This leads to uncertainty about the importance of a variety of physical phenomena including internal angular momentum transport, stellar winds, and disk locking in solar-like ( $M \sim 0.5$ – $1.5 M_{\odot}$ ) and lower mass stars (Krishnamurthi et al. 1997). Recent advances in theory (Sills, Pinsonneault, & Terndrup 2000) and observation (Terndrup et al. 2000; Bailer-Jones & Mundt 2001) have allowed us to investigate these issues to the H-burning limit and beyond. Stars with  $M < 0.5 M_{\odot}$  are of particular interest because they are fully convective and, therefore, likely to remain rigid rotators for a Hubble time, once they achieve that status. What has been missing in these studies is a knowledge of the “initial” (i.e., at  $\sim 1$  Myr) distribution of angular momentum as a function of mass, particularly for very low mass stars. This is important as a starting point for the studies mentioned and also as a test or guide for theories of protostar and early pre-main-sequence (PMS) evolution.

As usual, the best way to observe the time and mass dependence of a stellar parameter is by studying clusters. Investigations of stellar rotation have relied on a few nearby clusters, especially IC 2602,  $\alpha$  Persei, the Pleiades, and the Hyades, with ages ranging from 50 to 600 Myr. Angular velocities are directly determined by photometric monitoring. Large cool spots produce cyclical light variations as they rotate into and out of the line of sight. A Web-based compendium of photometric rotation periods for stars in these clusters has been compiled by C. F. Prosser and J. R. Stauffer.<sup>1</sup> The Orion Nebula cluster (ONC) represents an extremely important addition to these data for the following reasons: (1) its age is only  $\sim 0.8$  Myr (Hillenbrand 1997), placing

it among the youngest clusters known, (2) it is sufficiently dense and well populated that it will probably emerge from the formation process as a gravitationally bound entity (Hillenbrand & Hartmann 1998), making it directly comparable to the other clusters used in rotation studies, and (3) it is well populated with very low mass stars and brown dwarf candidates (Hillenbrand 1997; Hillenbrand & Carpenter 2000).

Rotational studies of low-mass stars in the ONC were pioneered by Mandel & Herbst (1991) and Attridge & Herbst (1992) who first showed that the solar-like stars had a bimodal distribution of rotation periods, similar to what is found in this mass range for the 50–150 Myr old clusters. Recent work has extended our knowledge of rotation to a larger mass range within the ONC and to the distributed population of PMS located throughout the Orion A molecular cloud (Choi & Herbst 1996; Stassun et al. 1999; Herbst et al. 2000; Rebull 2001; Carpenter & Hillenbrand 2001). Here we describe a further important extension to very low mass stars, all of which are within the ONC defined on dynamical grounds by Hillenbrand & Hartmann (1998). This is the relevant portion of the Orion association for direct comparison with older open clusters since it is the only part that will likely maintain its identity for 50 Myr or longer. Also, it is important to isolate a sample with as small an age range as possible in these studies since rotation periods may evolve rapidly during the first  $\sim 1$ – $2$  Myr of a star’s life. For these reasons, it is best to focus on the ONC, as opposed to the entire Orion A population (or other T associations), when studying the time dependence of stellar angular momentum using clusters.

### 2. OBSERVATIONS

Ninety-two images of the ONC were obtained through an intermediate-band filter ( $\lambda_c = 815.9$  nm;  $\Delta\lambda_{\text{FWHM}} = 20.9$  nm; selected to exclude strong nebular lines) on 45 nights between 1998 December 25 and 1999 February 22 with the Wide Field Imager attached to the MPG/ESO 2.2 m telescope at La Silla

<sup>1</sup> Available at <http://cfa-www.harvard.edu/~stauffer/opencl/index.html>.

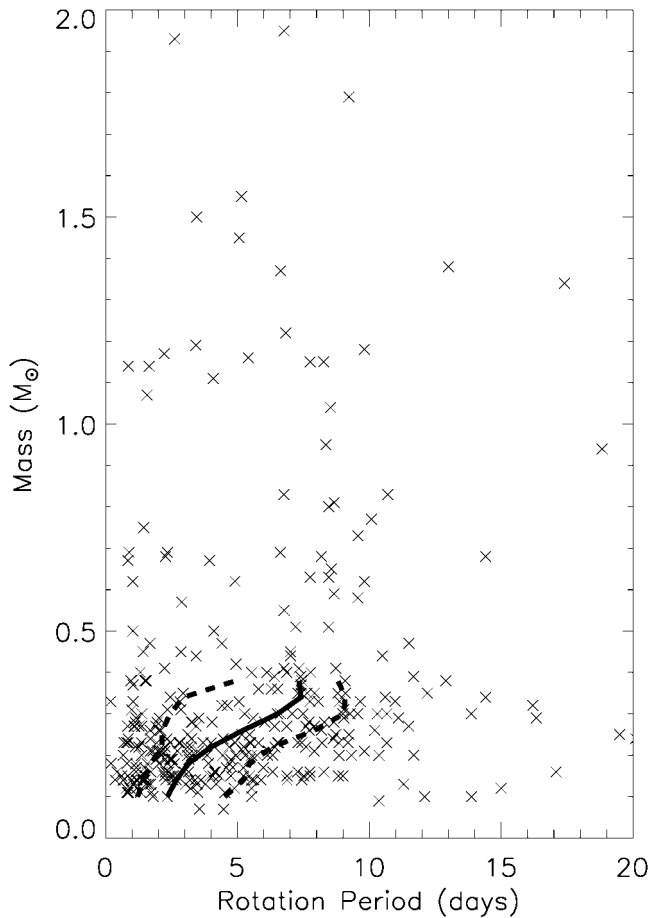


FIG. 1.—Rotation period vs. mass for stars in the ONC. The thick solid line is the moving median defined in the text, and the thick dashed lines are the corresponding quartiles. The moving median is not shown for  $M < 0.4 M_{\odot}$  because the relatively small number of stars makes it an unreliable statistic in that range.

in Chile. Details of the data acquisition, analysis, and additional results will be reported elsewhere (W. Herbst, C. A. L. Bailer-Jones, R. Mundt, K. Meisenheimer, R. Wackermann, & Ch. Wolf 2001, in preparation). Here we note that the field surveyed was a  $33' \times 34'$  rectangle centered approximately on  $\theta^1$  Orionis C, making it nearly coincident with the ONC defined by Hillenbrand & Hartmann (1998). Photometry was obtained on 2294 stars extending to  $I \sim 18$ . A search for periodicity was carried out using the Lomb-Scargle technique and standard assessments of false alarm probabilities (Herbst et al. 2000; Rebull 2001). Of the 404 periodic stars identified in our sample, 111 had been previously discovered by Herbst et al. (2000) or Stassun et al. (1999), and 99 of these were found to have identical periods to within the errors of the determinations ( $\sim 3\%$ ). A list of periodic stars is available on request to the first author. Eleven of the 12 stars that had period disagreements were cases of either harmonics or beat periods masquerading as fundamentals. The quality and quantity of the data obtained for this study are unprecedented, and that is responsible for our success in nearly tripling the number of rotation periods now known for stars in the ONC. In particular, our study extends to fainter stars and, therefore, lower masses than have been probed heretofore, and it is that aspect of the results that we primarily discuss in this Letter.

Figure 1 shows the distribution of rotation periods for 335

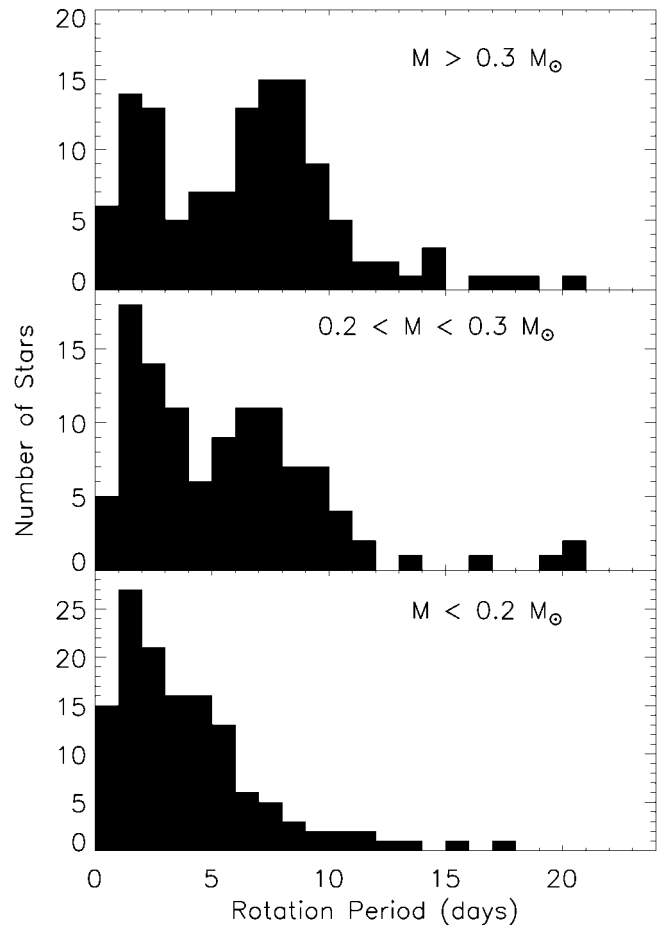


FIG. 2.—Rotation period distributions for stars in three mass ranges chosen to illustrate the data trends seen in Fig. 1. A bimodal distribution is clearly seen in the highest mass range, and a unimodal distribution consisting of rapid rotators is seen in the lowest mass range. The intermediate range shows a mixture of characteristics.

periodic stars in our sample that have masses determined by Hillenbrand (1997). Her determinations are based on a comparison of each star's location in the H-R diagram with PMS models of D'Antona & Mazzitelli (1994). Masses are, of course, model-dependent, and these could be systematically in error by perhaps as much as 50%. However, all models of PMS stars indicate that lower effective temperatures correspond to lower masses, so the sense of the variation of rotation with mass in Figure 1 is model-independent. It is evident in the figure that the range of rotation rates is very large, regardless of the mass range considered. While the extreme values on both the high- and low-period ends may be questionable (due to possible effects of aliasing and harmonics), it is fair to say that rotation periods in this cluster span at least a range of 0.8–12 days, independent of mass. What may be less obvious at first inspection, on account of that wide range, is that there is a definite change in the nature of the rotation period distribution with mass. Part of that trend is indicated by the thick solid line that shows the median period within a sliding sample defined by a mass range  $\pm 0.05 M_{\odot}$  at eight central values from 0.1 to  $0.4 M_{\odot}$ . This statistic and sampling interval were chosen for their robustness in the range of  $M < 0.4 M_{\odot}$ , which is the focus of this Letter.

To make the trends clearer and assess their statistical significance, we show, in Figure 2, histograms of the rotation period

distribution in three mass ranges. A double-sided Kolmogorov-Smirnov test indicates that the probability that the high-mass sample was drawn from the same parent population as the low-mass sample is less than  $3 \times 10^{-9}$ . This result is independent of the binning chosen to display the histograms. Clearly, the higher mass ranges show a bimodal distribution, as first discovered by Attridge & Herbst (1992) and later confirmed by Choi & Herbst (1996). Bimodality can be crudely quantified using the Double Root Residual test (Gebhardt & Beers 1991) that, in this case, indicates for the highest mass range that the distribution differs from uniformity at greater than the  $3 \sigma$  level. Clearly, the middle sample shows a mixture of attributes. We conclude that the rotation period distribution in the ONC is bimodal for stars with  $M \geq 0.25 M_{\odot}$  and unimodal for lower mass stars, confirming the results of Herbst et al. (2000). The interesting new result is that the majority of stars with  $M < 0.3 M_{\odot}$  clearly rotate faster than the majority of higher mass stars, and we turn now to a discussion of this issue.

### 3. ANALYSIS AND DISCUSSION

In an attempt to better understand these results, we first translate the observed quantity, rotation period  $P$ , into the fundamental physical quantity, specific angular momentum  $j$ . Assuming that convection enforces rigid rotation in low-mass stars, even at 1 Myr, the specific angular momentum of such a star with mass  $M$  and radius  $R$  is

$$j = \frac{J}{M} = \frac{I\omega}{M} = \frac{2\pi k^2 R^2}{P},$$

where  $J$  is the total angular momentum,  $I$  is the moment of inertia,  $\omega$  is the angular velocity, and  $k$  is the radius of gyration in units of the stellar radius. We assume homologous stars and adopt  $k = 0.44$ , appropriate to the 1 Myr old PMS models of Krishnamurthi et al. (1997). It follows that

$$j = \frac{6.82 \times 10^{16} (R/R_{\odot})^2}{P} \text{ cm}^2 \text{ s}^{-1},$$

where  $P$  is measured in days. A contracting PMS star will spin up roughly as  $P \propto R^2$  if it conserves angular momentum. At no time, however, can a star spin more rapidly than a balance between gravitational and centrifugal forces at its surface will allow. This criterion defines a critical period  $P_{\text{crit}}$  that applies to the axial rotation of a rigid sphere, namely,

$$P_{\text{crit}} = 0.116 \frac{(R/R_{\odot})^{3/2}}{(M/M_{\odot})^{1/2}} \text{ days},$$

which is  $\sim 0.5$  days for a  $2 R_{\odot}$ ,  $0.5 M_{\odot}$  PMS star. A corresponding critical specific angular momentum  $j_{\text{crit}}$  may be defined by inserting  $P_{\text{crit}}$  into the expression for  $j$  above.

In Figure 3, we show the observed value of specific angular momentum  $j_{\text{obs}}$  as well as  $j_{\text{crit}}$  for stars in our ONC sample. In calculating  $j_{\text{obs}}$  for  $M < 0.4 M_{\odot}$ , we have used the median period, shown in Figure 1, and the median radius (from Hillenbrand 1997) for the same moving samples. The dashed lines in this range show the locations of the quartiles of the sample (see also Fig. 1). For the higher mass stars, we show two values of  $j_{\text{obs}}$  corresponding to the two peaks in the period distribution, and we have adopted the model radii of D'Antona & Mazzitelli (1994) because the sample is too sparse to justify calculation of

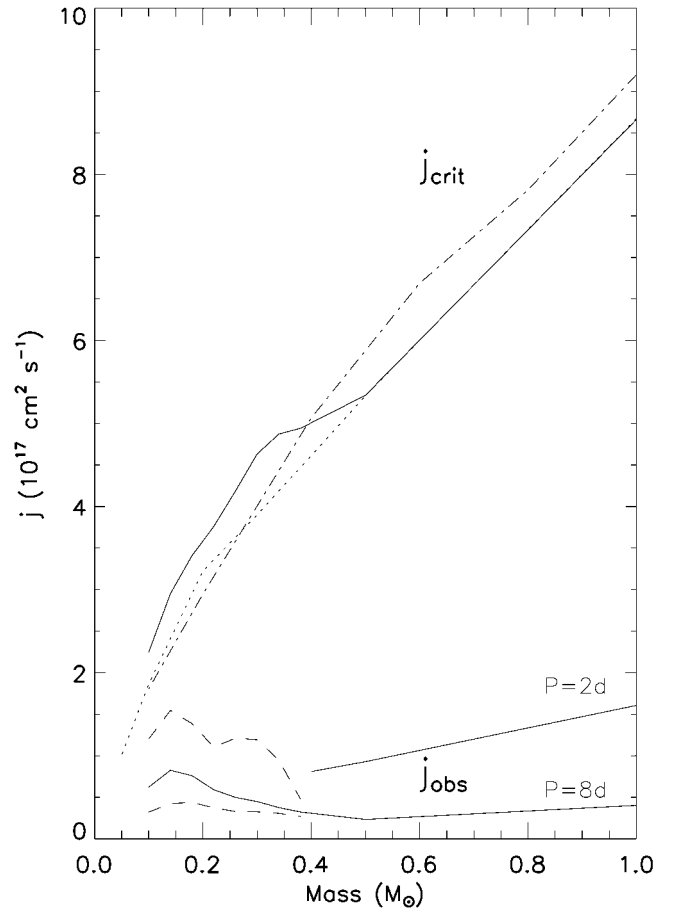


FIG. 3.—Specific angular momentum ( $j = J/M$ ) as a function of mass. The lower solid lines show the observations, including their bimodal character with periods of 2 and 8 days for  $M > 0.4 M_{\odot}$ . The dashed lines are an estimate of the uncertainty based on the quartile values (see Fig. 1). The upper solid line shows the value of  $j_{\text{crit}}$  for a rigid sphere with the mass and radius (calculated as a moving median over the same sample described in the text) rotating at its critical velocity. The dotted and dash-dotted lines show  $j_{\text{crit}}$  for model PMS stars from D'Antona & Mazzitelli (1994) and Palla & Stahler (1999), respectively, rotating at critical velocity. It is clear from this figure that lower mass stars rotate at a greater percentage of their critical angular velocity than do higher mass stars in the ONC.

a moving median. It is clear from this figure that the specific angular momentum of a “typical” PMS star shows very little dependence on mass over the one decade interval of  $0.1$ – $1.0 M_{\odot}$ . Here we define “typical” as a star having the median rotation rate at lower mass or having  $P \sim 8$  days at higher mass. (As Fig. 1 shows, about two-thirds of the higher mass stars in the ONC fall in the slower rotating peak of the period distribution.) There is evidence for a small (factor of  $\sim 2$ ) increase in  $j$  with decreasing mass in the range  $0.1 M_{\odot} < M < 0.4 M_{\odot}$ , although a constant value is only barely inconsistent with the errors.

Three estimates of  $j_{\text{crit}}$  are also shown in Figure 3 for comparison with the observations. It may be seen from the expressions above that  $j_{\text{crit}} \propto (MR)^{1/2}$ , so it requires masses but is not highly sensitive to them. The values represented by the solid lines correspond precisely to the observations. That is, for  $M < 0.4 M_{\odot}$ , they are based on the same moving median samples, with radii and masses taken from Hillenbrand (1997), and for the higher mass stars, they are based entirely on the 1 Myr old models of D'Antona & Mazzitelli (1994). The model

results are shown extended into the low-mass range by the dotted line in Figure 3, revealing only a small difference, as expected. To check whether a completely different set of models would give similar results, we also show, as a dash-dotted line, calculations of  $j_{\text{crit}}$  based on the 1 Myr old PMS models of Palla & Stahler (1999). Clearly, the results are in good agreement and indicate a significant trend of decreasing  $j_{\text{crit}}$  with decreasing mass.

It is clear from Figure 3 that lower mass stars in the ONC rotate at closer to their critical rates than do their higher mass counterparts. Specific angular momentum exceeds 25% of the critical value for the lowest masses ( $M \sim 0.1 M_{\odot}$ ) in our sample, compared with  $\sim 5\%$ , which is typical of solar-like stars. This result is model-dependent in the sense that the  $j_{\text{obs}}$  curve would translate along the mass axis if different models were employed to infer masses from the luminosity and effective temperature. However, the general shape of the curve (i.e., fairly flat) is independent of the PMS model chosen for this transformation. The observed value of  $j_{\text{obs}}$  depends only on  $P$  and  $R$ , and  $R$  is determined from the luminosity and effective temperature without reference to stellar models. (If there were a mass-dependent systematic error in  $R$ , this would affect the shape of  $j_{\text{obs}}$ , but that possibility is not given serious consideration here.) We conclude, therefore, that lower mass stars in the ONC rotate at rates much closer to their critical angular velocity than higher mass stars, and they do so for two reasons. First,  $j$  increases somewhat at lower masses, or at the very least remains constant, and second,  $j_{\text{crit}}$  decreases with mass, which is mainly a result of the decrease in radius predicted by the models.

Our observations in the ONC are interesting from two perspectives. First, they can serve as the initial conditions for theoretical models of angular momentum evolution that may ultimately account for the 30–600 Myr old cluster data. The calculation of such models is beyond the scope of this Letter. Here we note, however, that the basic features of the angular velocity distribution with mass in the Pleiades recently discussed by Terndrup et al. (2000) are rather precisely mimicked in our data on the ONC. In particular, both clusters exhibit a bimodal period distribution for more massive stars and a unimodal distribution with increasingly rapid rotation at lower

masses. The mass at which the nature of the distribution changes is, possibly, higher in the Pleiades but could be the same, given the large uncertainties in both clusters. In any event, these data suggest that future studies of rotational evolution of low-mass stars such as that of Sills et al. (2000) should consider a mass-dependent starting angular velocity.

The second issue raised by our data is this: can we understand the ONC rotation distribution in terms of the mechanism(s) that establish the “initial” angular momentum of a star during the first  $\sim 1$  Myr of its life? Bodenheimer (1995) has reviewed those mechanisms, and it is clear that the mass dependence, or lack of a strong one, reported here could be an important clue to sorting out the relevant processes. It has long been thought that magnetic fields must play a key role in removing angular momentum from protostars and PMS stars. This view is certainly supported by the fact that we detect the spot variations of PMS stars; they must have large, stable cool spots on their surfaces, and this is *prima facie* evidence that they have strong, well-organized magnetic fields. The disk-locking mechanism of Camenzind (1990), Königl (1991), and Shu et al. (1994) provides a plausible explanation for the fact that  $\omega \approx 0.05\omega_{\text{crit}}$  for a typical T Tauri star of  $0.5 M_{\odot}$  (Ostriker & Shu 1995). It also accounts nicely for the bimodal distribution of the more massive ONC stars (Choi & Herbst 1996; Herbst et al. 2000) and for the wide range in angular momenta of cluster stars (Barnes, Sofia, & Pinsonneault 2001). Could it also explain the fact that lower mass stars in the ONC (and the Pleiades) rotate more rapidly, but with only slightly enhanced or, perhaps, a constant value of  $j$ ? It is not obvious to us that there is anything fundamental in the disk-locking theory that predicts a weakly mass-dependent rotation law of the form we observe, but we suspect that it could easily accommodate one. We leave these considerations to future investigations, with the hope that the observational guidance provided here may prove useful in understanding the complex issues of angular momentum transport during the PMS phase.

We thank S. Barnes for helpful discussions on the topic of this Letter. It is a pleasure to thank K. Meisenheimer, R. Wacker-ermann, and Ch. Wolf for assistance with the observations. This work was partially supported by a grant from the NASA Origins program.

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