We present the results of a monitoring campaign aimed at deriving rotation periods for a representative sample of stars in the young (30 Myr) open cluster IC 2602. Rotation periods were derived for 29 of 33 stars monitored. The periods derived range from 0.2 days (one of the shortest known rotation periods of any single open cluster star) to about 10 days (which is almost twice as long as the longest period previously known for a cluster of this age). We are able to confirm eight previously known periods and derive 21 new ones, delineating the long-period end of the distribution. Despite our sensitivity to longer periods, we do not detect any variables with periods longer than about 10 days. The combination of these data with those for IC 2391, an almost identical cluster, leads to the following conclusions: (1) The fast rotators in a 30 Myr cluster are distributed across the entire $0.5 < B - V < 1.6$ color range. (2) Six stars in our sample are slow rotators, with periods longer than 6 days. (3) The amplitude of variability depends on both the color and the period. The dependence on the latter might be important in understanding the selection effects in the currently available rotation period database and in planning future observations. (4) The interpretation of these data in terms of theoretical models of rotating stars suggests both that disk interaction is the norm rather than the exception in young stars and that disk-locking times range from zero to a few Myr.

Subject headings: circumstellar matter — open clusters and associations: individual (IC 2602) — stars: evolution — stars: pre-main-sequence — stars: rotation — stars: variables: other

1. INTRODUCTION

IC 2602 is a young (30 Myr old) open cluster in the southern hemisphere [α(1950) = 10°41′m, δ(1950) = −64°]. At a distance of about 150 pc, it is one of the nearest open clusters. For the brightest members, Whiteoak (1961) and Braes (1962) provided photographic and photoelectric photometry, and spectral types were also derived for some of the brighter candidates using low-dispersion spectroscopy by Whiteoak (1961) and Abt & Morgan (1972). Braes (1962) also provided proper-motion membership for some of the bright members of the cluster. Despite its proximity, no information was available for the low-mass stars in the cluster until very recently.

Unfortunately, no proper-motion membership is currently available for the late-type stars in IC 2602, and studies of this cluster have had to overcome this obstacle in various ways. A ROSAT X-ray survey of IC 2602 reported by Randich et al. (1995) identified several candidate low-mass members. This work was followed by additional photometry (Prosser, Randich, & Stauffer 1996), $v \sin i$ measures and spectroscopic confirmation of membership (Stauffer et al. 1997), and lithium abundances (Randich et al. 1997) for these low-mass members and candidate members. Rotation period measurements, which are preferred to those of $v \sin i$ because they provide the unambiguous measure of a given star’s angular velocity, have been provided for a few members of this cluster by Patten, Stauffer, & Prosser (1996) and C. F. Prosser (1997, private communication) but no substantial sample of rotation periods has yet been published for this cluster.

IC 2602 is particularly interesting from the point of view of studying stellar rotation because it affords a sample of stars that have just descended the Hayashi track but have not yet experienced main-sequence angular momentum loss. Thus, they can illustrate the distribution of rotational velocities among pre-main-sequence stars. Although data exist for two slightly older clusters, $\alpha$ Per (Stauffer et al. 1985, 1987; Prosser et al. 1993a, 1993b, 1995; O’Dell & Cameron 1993; Bouvier 1996; Prosser & Grankin 1997) and the Pleiades (Van Leeuwen & Alpenhaar 1982; Van Leeuwen, Alpenhaar, & Meys 1987; Stauffer et al. 1987; Prosser et al. 1993a, 1993b, 1995; Krishnamurthi et al. 1998), data for stars in IC 2602 (30 Myr) should prove to be particularly useful in trying to understand the evolutionary progression of stellar rotation from T Tauri stars (few Myr) to the 50 and 70 Myr ages of $\alpha$ Per and the Pleiades, respectively. Moreover, because of the speed with which rotation changes on the pre-main sequence, the differences between these clusters might turn out to be important.

Although $v \sin i$ observations exist for IC 2602 (Stauffer et al. 1997), these measurements are affected by the unknown angle of inclination, $i$, and the uncertainties in determining stellar radii. Rotation periods are not affected by these uncertainties, and thus they provide more useful
rotational information. However, greater effort is involved in determining rotation periods than in obtaining \( v \sin \, i \) measures, a fact that generally limits the number of period derivations obtained for stars. Typically, only one-half to three-quarters of the stars with measured \( v \sin \, i \) values yield a rotational period. On the positive side, an additional advantage of measuring rotation periods is that it is possible, if one has the appropriate time coverage, to measure them even for stars with only \( v \sin \, i \) upper limits.

One of the most puzzling issues to understand in connection with the rotation rates of stars in young open clusters is the question of the simultaneous existence of both ultrafast and slow rotators in the same clusters. Although some data exist for the similarly young cluster IC 2391 (Patten & Simon 1996), they are by no means an adequate sample. In particular, because of the typical duration of observing runs (usually a week or two), it has not been possible to answer the question of how slow the slowest rotators in clusters of this age are. The answer to the question is of great importance in understanding the extent of the effect of disk regulation of stellar rotation on the Hayashi track. The ultrafast rotators (UFRs), on the other hand, tell us about the necessity and extent of magnetic saturation in these stars. Thus it is vitally important to obtain a large, unbiased sample of rotation information for these stars. In this regard, we have undertaken a survey (of the rotational properties) of the low-mass membership of the IC 2602 open cluster in an effort to delineate as much as possible the rotational velocity distribution ranging from the UFRs to the slowly rotating members having only upper limits on \( v \sin \, i \).

2. OBSERVATIONS AND DATA ANALYSIS

Because of its far southern location, IC 2602 has received less attention than it might otherwise have. Its proximity enables us to monitor its late-type stars with a small (1 m class) telescope. On the negative side, this proximity results in a large apparent cluster size of \( \sim 100 \) (Lynga 1985), and therefore a monitoring program cannot be designed to accommodate many program stars on a single exposure.

In order to avoid unnecessary biases in the selection of candidates to monitor, we have elected to monitor every previously spectroscopically confirmed cluster member from Stauffer et al. (1997) with \( B - V > 0.5 \). It is probably worthwhile to add that the membership assessments in Stauffer et al. (1997) for each of the program stars were made after careful consideration of the X-ray emission, photometry, position in the color-color diagram, spectroscopy, and, where available, lithium abundance. The reader is referred to that publication (and references therein) for further details regarding the cluster membership criteria.

ICD images were taken in the \( V \) band of 23 fields in IC 2602 with the 0.9 m telescope at Cerro Tololo Inter-American Observatory in 1995 March, April, and May. They were monitored about once a night for a week (1995 March 18–25). Then, after a gap of about a week, they were observed more intensively for about 3 weeks (1995 April 4–24) with a frequency dictated by weather and other observing project constraints, but nominally at the rate of 3–4 times per night. In addition, a subset of them were monitored, some intensively, by C. P. during 1995 May 8–21. The data taken by C. P. were binned 2 \( \times \) 2 pixels, whereas the other data were unbinned with a resolution of 0.4 per pixel. The total number of sampling points for each star varied, depending on the intensity of the observing effort, from 42 images for R68 to 155 images for R88A. As far as observing constraints allowed, we have tried to sample the light curves of individual stars over the course of the run in a manner that would minimize aliasing at 1 day intervals. However, as the light curve for R32 (period \( \sim 4 \) days) demonstrates, it has not always been possible to sample a star over all phases.

After CCD processing, including bias subtraction and flat-fielding, using IRAF, instrumental magnitudes were measured by fitting point-spread functions (PSFs) to the stars on each frame using DAOPHOT II and ALLSTAR II (Stetson, Davis, & Crabtree 1991). Stars on or sufficiently near bad columns were ignored. The photometry from the individual frames was converted into time series using the DAOMATCH/DAOMASTER routines from Stetson (1992). These routines match stars appearing in multiple images according to user-supplied specifications, calculate the photometric offsets between frames, and output the corrected time series. The uncertainty in the frame-to-frame magnitude offsets was less than 0.003 mag for the frames that were eventually used because of the large number of stars matched from frame to frame. The PSF fitting procedure resulted in individual star magnitudes that had formal errors of \( \sim 0.01 \) mag for the unbinned data and \( \sim 0.02 \) mag for the binned data.

This procedure, although CPU intensive, obviates the necessity of choosing a few comparison stars for each program star and checking each of them in turn for variability or for other problems. The virtue of PSF fitting is that one need not worry about crowding, and cosmic rays are handled a little more gracefully than in aperture photometry. A negative is that on nights with particularly bad seeing, we may have blends of nearby stars. We have usually chosen to discard data acquired under such conditions. The use of an ensemble of stars instead of a few hand-picked ones for reference propels the study of stellar variability from the “retail” to the “wholesale” arena. It also allows us to check any other objects in the image for variability, if we so choose. Indeed, this technique has been employed to discover approximately 50 variables in a field centered on the open cluster NGC 3680 (Platais & Barnes 1999).

Three techniques were used to search for periodicity in the IC 2602 target stars—the phase dispersion minimization technique of Stellingwerf (1978), the periodogram technique of Scargle (1982), and the CLEAN algorithm of Roberts, Lehar, & Dreher (1987). We have usually run 100 CLEANs with a gain of 0.1 and have searched for periodicity in the nominal frequency range \( 0–10 \) per day. We do not expect any of the program stars to rotate any faster than 10 times a day (Barnes & Sofia 1996). Among low-mass stars, the shortest period known so far is 4.4 hr for AP 124 in the \( \alpha \) Per cluster (Prosser et al. 1993b). As for the low-frequency end, since our sampling extends to over 60 days in some cases, we expect to be able to detect up to a monthly variability in those fields. For the most sparsely

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4 Disk regulation describes the coupling, via magnetic fields, of the central star (and hence its rotation) to the young circumstellar disk. Edwards et al. (1993) presented good evidence that disk regulation explained the difference in rotation periods between classical and naked T Tauri stars, and this has become the widely accepted paradigm.
For almost all stars whose light curves are provided in this work, the variability was observed in the output of all three techniques. In a few cases, CLEAN was able to pick out a preferred signal where none could be found using the techniques of either Stellingwerf or of Scargle. Once a signal is detected, the evaluation of whether the period is believable or not must be made by considering the strength of the spike in the power spectrum, the variability apparent in the raw light curve, and the appearance of the phased light curve. For most of the stars with periodic variations, the variability was happily obvious from the raw light curve and the spectral analysis only served to determine the period precisely.

Table 1 summarizes the data for each of the stars monitored in IC 2602. Columns (1)–(4) identify the star in question and display the photometry from Prosser et al. (1996) and Randich et al. (1995). Column (5) gives the $v \sin i$ measurement in km s$^{-1}$ from Stauffer et al. (1997). Column (6) gives the number of observations obtained for each star and, in parentheses, the time baseline representing the difference in HJD between the first and last observations. Columns (7) and (8), respectively, give our period (with the error) and the previous period, if any, from Patten et al.

### Table 1

**Data Summary for IC 2602 Stars**

| Name | $V$ | $B-V$ | $(V-I)_c$ | $v \sin i$ | $N_{\text{obs}}$ (Baseline [days]) | Period (days) | $P_{\text{prev}}$ (days) | $N_v$ | $L_v/L_{\text{bol}}$ | Variability Amplitude (mag) | $n(Li)$ |
|------|-----|-------|-----------|------------|----------------------------------|---------------|----------------|------|-----------------|---------------------------|--------|
| B134 | 10.66 | 0.95 | 1.00 | 10 | 61 (64) | 6.8±0.3 | ... | ... | 0.110 | −3.69 | 0.025 | ... |
| W79  | 11.57 | 0.83 | 0.85 | 8 | 61 (37) | 6.2±0.5 | ... | ... | 0.117 | ... | 0.02 | ... |
| R15  | 11.75 | 0.93 | 1.06 | 7 | 41 (37) | 3.6±0.2 | ... | ... | 0.059 | −2.96 | 0.01 | 2.56 |
| R21  | 9.50  | 0.51 | 0.62 | 23 | 37 (37) | ... | ... | ... | ... | −3.83 | ... | 3.32 |
| R24A | 14.61 | 1.43 | 1.86 | 34 | 93 (64) | 1.25±0.01 | ... | 0.013 | −3.07 | 0.06 | ... | ... |
| R26  | 15.14 | 1.54 | 2.15 | <6 | 93 (64) | 5.7±0.3 | ... | 0.056 | −3.57 | 0.05 | ... | ... |
| R27  | 14.35 | 1.50 | 1.80 | 10 | 57 (64) | 4.5±0.2 | ... | 0.045 | −3.57 | 0.035 | ... | ... |
| R29  | 12.73 | 1.11 | 1.19 | 22 | 77 (64) | 2.21±0.04 | 2.19 | 0.031 | −3.21 | 0.05 | 1.76 | ... |
| R31  | 15.08 | 1.59 | 2.24 | 35 | 83 (64) | 0.49±0.01 | ... | 0.005 | −2.94 | 0.02 | ... | ... |
| R32  | 15.06 | 1.63 | 2.16 | 9 | 39 (51) | 4.0±0.2 | ... | 0.035 | −3.16 | 0.075 | ... | ... |
| R38  | 15.72 | 1.53 | 2.50 | 48 | 92 (64) | ... | ... | ... | −3.10 | ... | ... | ... |
| R43  | 12.14 | 0.95 | 1.10 | 50 | 42 (53) | 0.78±0.01 | 0.78 | 0.013 | −3.01 | 0.035 | 3.17 | ... |
| R44  | 14.88 | 1.55 | 2.03 | 7 | 57 (64) | 5.5±0.2 | ... | 0.053 | −3.60 | 0.04 | ... | ... |
| R50  | 14.75 | 1.56 | 2.08 | 7 | 80 (64) | 6.4±0.4 | ... | 0.061 | −3.19 | 0.02 | ... | ... |
| R52  | 12.19 | 1.07 | 1.11 | 95 | 76 (64) | 0.393±0.002 | 0.393 | 0.006 | −3.33 | 0.07 | ... | ... |
| R53B | 15.39 | 1.61 | 2.49 | 100 | 58 (53) | 0.41±0.01 | ... | 0.004 | −3.12 | 0.045 | ... | ... |
| R56  | 13.64 | 1.43 | 1.60 | 17 | 88 (64) | 4.1±0.1 | ... | 0.043 | −2.99 | 0.055 | <0.65 | ... |
| R57  | 15.59 | 1.60 | 2.44 | <6 | 40 (37) | 8.7±0.9 | ... | 0.079 | −3.30 | 0.02 | ... | ... |
| R58  | 10.57 | 0.65 | 0.76 | 93 | 108 (64) | 0.57±0.01 | ... | 0.015 | −3.22 | 0.055 | 3.55 | ... |
| R66  | 11.07 | 0.68 | 0.83 | 12 | 39 (51) | 3.3±0.2 | ... | 0.082 | −3.76 | 0.035 | 3.10 | ... |
| R68  | 11.28 | 0.89 | 1.09 | 48 | 42 (37) | ... | ... | ... | −3.03 | ... | ... | 2.90 |
| R70  | 10.92 | 0.69 | 0.71 | 11 | 63 (64) | 4.3±0.1 | ... | 0.107 | −4.44 | 0.02 | 2.95 | ... |
| R72  | 10.89 | 0.64 | 0.76 | 49 | 65 (63) | 1.05±0.02 | ... | 0.029 | −3.01 | 0.035 | 3.41 | ... |
| R77  | 14.12 | 1.47 | 1.72 | <7 | 70 (64) | 10.1±0.9 | ... | 0.104 | −3.66 | 0.03 | ... | ... |
| R83  | 10.70 | 0.62 | 0.78 | 30 | 135 (64) | 1.67±0.01 | ... | 0.049 | −3.55 | 0.035 | 3.45 | ... |
| R85  | 9.87  | 0.52 | 0.58 | 45 | 110 (64) | ... | ... | ... | −4.74 | ... | 3.17 | ... |
| R88A | 12.71 | 1.20 | 1.35 | 200 | 135 (64) | 0.204±0.001 | 0.204 | 0.003 | −3.54 | 0.04 | ... | ... |
| R89  | 12.97 | 1.24 | 1.35 | 14 | 51 (37) | 4.8±0.3 | 4.47 | 0.059 | −3.49 | 0.065 | 1.60 | ... |
| R92  | 10.26 | 0.67 | 0.78 | 14 | 34 (37) | 2.0±0.1 | ... | 0.050 | −3.72 | 0.015 | 3.12 | ... |
| R93  | 13.79 | 1.37 | 1.62 | 8 | 53 (64) | 6.7±0.4 | ... | 0.075 | −3.60 | 0.025 | ... | ... |
| R94  | 13.33 | 1.39 | 1.73 | 23 | 48 (64) | 2.6±0.1 | ... | 0.028 | −3.56 | 0.035 | <0.87 | ... |
| R95A | 11.73 | 0.87 | 0.97 | 12 | 51 (51) | 1.20±0.02 | 1.23 | 0.021 | −2.90 | 0.04 | 3.23 | ... |
| R96  | 12.94 | 1.25 | 1.37 | 17 | 36 (37) | 1.82±0.05 | 1.81 | 0.022 | −3.18 | 0.05 | ... | ... |

5 In this figure and in several following ones, we have chosen to mark the stellar positions in the graph with the names of the stars themselves for ease of comparison across graphs.
We have determined rotation periods for 29 stars (three of which are provisional) out of the 33 that were monitored. This is a very high success rate and attests to the efficacy of our technique. The high success rate for period detection may also be traced to the relative youth (and hence high activity) of the cluster stars. The phased light curves show clearly that almost all the stars are heavily spotted. The periods detected range from about 0.2 days (R88A) to 10.1 days (R77). We believe that these data do not suffer from any selection effects related to the length of the observing run. Although the longest period discovered among the stars monitored is only about 10 days, the length of our observing program ensures that we are able to detect at least 15 day periods comfortably in all the observed fields and up to 30 day periods in several cases.⁶

A few words about period sensitivity are in order here. Although it is clear that one cannot detect a period longer than the baseline of observations (in this case, 64 days), deciding on the longest detectable period for unevenly spaced data is a matter of opinion. If the light modulation is large enough and repeats perfectly and the sampling is good enough, one might expect to be able to detect even 60 day periods, since the overlap on the last 4 days would be obvious. In practice, light modulation from spotted stars is not perfectly repeatable because spots evolve and sampling is almost nonuniform. If the investigators are conservative they might demand, as we have, coverage over two complete cycles, but clearly longer periods, up to the baseline of the observations, are detectable with good sampling.

Of the four remaining stars without periods, we suspect that R38 and R68 have rotation periods of 0.79 and 0.66 days, compatible with the \( v \sin i \) measurements of 48 km s\(^{-1}\). We do not trust these rotation periods enough to include them in any of the further analysis. The remaining two, R21 and R85, are the bluest stars in the sample. Our failure to detect variability for these two stars might simply be an indication that they do not have large enough spots and therefore would have lower variability amplitudes. Their \( v \sin i \) values of 23 and 45 km s\(^{-1}\), respectively, are certainly large enough that one might expect variability were they redder stars.

3.2.1. Comparison with \( v \sin i \) Measurements

Figure 4a displays our rotation period measurements against the \( v \sin i \) measurements of the same stars by Stauf-

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⁶ In fact, we have discovered a variable in the field of R88A that has a period of about 43 days.
Fig. 2.—CLEANed spectra for the 29 variable stars for which we have determined rotation periods. Stars are arranged in order of increasing $V$ mag, right to left and top to bottom. The frequency ($x$) scale ranges from 0 to 5 cycles day$^{-1}$. The power ($y$) axes are arbitrary.
Fig. 3.—Phased light curves for stars in IC 2602 for which we have been able to derive rotation periods. Two phase cycles are plotted, brightest points at the top. The magnitude (y) axes are arbitrary but the scale bar shown in each panel corresponds to 0.01 V mag.
fer et al. (1997). The arrows indicate $v \sin i$ upper limits for three stars, R26, R57, and R77, for which we have now been able to derive periods. The trend of shortening period with increasing $v \sin i$ is, as expected, clear, and no object is located in the top right-hand corner. This information, of course, makes it possible in principle to calculate the angles of inclination of individual stars. We refrain from doing so because the errors are large when we consider the uncertainties in the values of the radii of individual stars, along with uncertainties in the $v \sin i$/period measures. However, it is possible to identify by inspection stars with small and large angles of inclination and to examine whether the light curves of these stars are indeed consistent.

Stars located along the lower envelope of the points plotted in Figure 4a have lower than average $v \sin i$ values that indicate either or both of (1) a small star and (2) small $i$. For the larger and hence bluer ($B - V < 1.0$) of these stars, a low $v \sin i$ value must therefore indicate a smaller inclination angle and this should be correlated with what is seen in the corresponding power spectrum, light curve, and amplitude of variability. Conversely, $v \sin i$ values along the upper envelope in Figure 4a indicate either or both of (1) a large star and (2) large $i$, unless they are also associated with unusually short rotation periods. Thus, for the smaller and hence redder of these stars ($B - V > 1.2$), a high $v \sin i$ value would indicate a large angle of inclination. We have examined these issues in relation to these data and indeed have found no inconsistency.

3.2.2. Color Dependence of the Rotation Periods

Perhaps the most interesting question, and the main motivation for this study, is how the rotation periods of the IC 2602 stars vary as a function of color. The mass dependence of the rotation period distribution is particularly important because models of stellar rotation make predictions of what it might be, and this information may be used to test them. These data are particularly useful because they give us a snapshot of rotation for solar and late-type stars at 30 Myr. At this point in their evolution, the IC 2602 stars have descended the Hayashi track and have ceased to interact strongly with their disks, but have not yet experienced main-sequence angular momentum loss.

The rotation periods we have derived for our sample of IC 2602 stars (including the provisional determinations) are plotted in Figure 4b as a function of the $B - V$ color. Each data point is, as before, plotted using the name of the star and is to be considered as lying at the lower left corner of the name.

One of the features of the data in Figure 4b (which becomes even more obvious when the IC 2391 data are combined, as in Fig. 8) is the uniformity of rapid rotation across the color range under consideration. Data in the slightly older open cluster z Per suggested this for the $0.65 < B - V < 1.25$ (approx. $1 < M/M_\odot < 0.8$) range. These data, when combined with those for IC 2391 (Patten & Simon 1996), extend this observed behavior over the range $0.5 < B - V < 1.6$ (approx. $1.2 < M/M_\odot < 0.6$). This feature of the observations is related to magnetic saturation (e.g., Barnes & Sofia 1996) and will be discussed in § 4, as will another obvious feature of these data—the greater dispersion in rotation period among the lower mass stars.

A relatively surprising feature of these data is the length of the rotation periods of the slow rotators, which extend to about 10 days. Although there are five stars in the Pleiades ($\simeq 70$ Myr old) with 7–8 day periods and one with an approximately 10 day period, such slow rotation was not expected in a cluster that is only half as old. Rotation periods among T Tauri stars are known to extend to about 16 days (with the tail end of the distribution extending to even longer periods) but these stars are expected to spin up significantly during pre–main-sequence evolution. The slowest rotator known in IC 2391, which is also only about 30 Myr old and is generally considered as a twin to IC 2602, has a period less than 6 days (Patten & Simon 1996). In IC 2602, however, six stars, representing about a fifth of our sample, have periods longer than 6 days. The authors opine that small samples and short observing runs have conspired to prevent this fact from being discovered earlier. It is important to have a long enough observing run to ferret out the slow rotators. If theoretical models (e.g., Barnes, Sofia, & Pinsonneault 1999; Barnes 1998) are to be believed, the existence of these slow rotators cannot be understood simply by evolving the slowest T Tauri stars forward in time, but requires the additional slowdown provided by a star-disk interaction on the pre–main sequence.

We can, in fact, use these data to make a somewhat stronger point than the one made in the foregoing para-
graph. The two slowest rotators, R57 (8.7 days) and R77 (10.1 days), are both quite red, with $B - V$ of 1.60 and 1.47, respectively. The trend of increasing period with reddening color is the dominant one in the Hyades data (Radick et al. 1987) but is not obvious in measurements of younger open clusters. Some of this may be ascribed to small sample sizes, but much of it is probably related to the youthfulness of these clusters relative to the Hyades and to difficulties associated with deriving rotation periods for very slow rotators. The IC 2602 sample is also a small one, but the fact that the slowest rotators are also among the reddest stars in the sample is probably worth noting.

In summary, the rotation period data in IC 2602/IC 2391 indicate that the ultrafast rotators are distributed across the range $0.5 < B - V < 1.6$. We have also derived periods for several slow rotators and note that the slowest rotators have redder colors.

### 3.3. Variability Amplitude

The amplitude of variability (in $V$ mag) of these stars is plotted in Figure 5a as a function of the $B - V$ color. Contrary to expectations that earlier type stars, because they are usually not as heavily spotted as their lower mass counterparts, might have smaller variability amplitudes, no strong dependence is immediately obvious from these data. This could be an indication that all of the IC 2602 (and IC 2391) stars are so young and hence still so active that the differences between the earlier and later type stars is not yet obvious. This viewpoint seems to be supported by the X-ray data, which is discussed in the following section.

There is, however, a weak trend in these data that merits attention. If we divide Figure 5a into four quadrants, blueward and redward of $B - V = 1.0$ and variability amplitudes less than and greater than 0.04 mag, only R58 appears in the second quadrant. This star is peculiar because in S. B.'s data it set its variability amplitude was only 0.02, whereas in C. P.'s data it has the much larger variation that is plotted in Figure 5a. Regardless of the position of R58, one can make the following statement: The majority of the blue stars have variability amplitudes less than 0.04 mag, whereas the majority of the red stars have amplitudes in excess of this. The conclusion seems to be bolstered slightly by the additional data available in IC 2391 (Patten & Simon 1996), which is plotted in Figure 5 using open circles. It will be interesting to examine whether it will continue to hold when larger data sets become available.

The above viewpoint receives support in Figure 5b, which displays the amplitude of variability as a function of rotation period. This figure clearly separates the IC 2602 stars into two distinct groups. The ones with periods shorter than 6 days show a wide range in the amplitude of variability, from 0.01 to 0.08 $V$ mag. Those with longer periods all have amplitudes less than or equal to only 0.03 mag. This is highly relevant to period determinations in older clusters because it suggests that it will be difficult to detect variability in similar stars when they are older and their activity has decreased.

Interestingly, all the long-period stars (with small variability amplitudes) are later types with $B - V > 1.0$, and this despite the fact that late-type stars have greater amplitudes of variability on average than early-type ones. Also, among the stars with periods shorter than 4 days, every single star (with the exception of R58) that has an amplitude greater than 0.04 mag is a red star. The blue stars are not as variable as we saw above. This suggests that if a blue star were a slow rotator, it would probably go undetected in the present period searches. Our sample does not contain such a star.

The information contained in the foregoing two figures can be combined together by displaying the variability amplitude as a function of Rossby number. For completeness, we have displayed this information for our sample of stars in IC 2602 in Figure 5c. From the viewpoint of the Rossby number calculation, the rotation period dependence appears directly in the numerator, and the color dependence of the variability appears in the denominator via the convective turnover timescale, which is an equivalent variable for these purposes. We have used the convective turnover timescale provided by Kim & Demarque (1996).

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7 The Rossby number is defined as $P_{\text{rot}}/\tau_c$, where $P_{\text{rot}}$ and $\tau_c$ represent the (observed) rotation period and the (calculated) convective turnover timescale, respectively.
3.4. X-Rays

The connection between rotation and X-ray emission is particularly interesting in view of the concept of magnetic saturation, which suggests that a stellar magnetic field does not increase indefinitely with a star's angular velocity, but saturates beyond a threshold value that varies from star to star in a manner not yet understood.\(^8\)

Some intriguing observational evidence in support of magnetic saturation was provided by Staufer (1994) and Staufer et al. (1994), who noticed that the X-ray emission (which is widely regarded as an indicator of magnetic field strength) of individual stars in the Pleiades has a wide range for stars with low \(v \sin i\) values, but stays relatively constant at an elevated level for those with high values. Models that included saturation were calculated by Chaboyer, Demarque, & Pinsonneault (1997) and others, but the results were ambiguous because the models did not start high enough on the Hayashi track and plentiful observations were not available then. The idea received a further boost when it was realized (Barnes & Soffia 1996; Krishnamurthi et al. 1997) that theoretical models of rotating stars that started at the stellar birth line also could not explain the existence of the ultrafast rotators in young star clusters without incorporating the idea of magnetic saturation (with a threshold that varied with stellar mass).

Given the extensive X-ray coverage of this cluster and the considerable interest in stellar activity, it might be worthwhile to examine how these data relate to the X-ray properties of this cluster. The X-ray data (Randich et al. 1996) have played a crucial part in the study of this cluster by taking over the role usually played by a proper-motion study. The stars identified as candidate members of the cluster by the X-ray data have been studied photometrically (Prosser et al. 1996) and spectroscopically (Staufer et al. 1997), to a point that we are now reasonably certain about the cluster membership.

This raises the issue of whether the IC 2602 members also show signs of magnetic saturation. Figure 6a displays the distribution of \(\log (L_x/L_{bol})\) as a function of the observed rotation periods from Table 1. It is clear that many of the stars are operating in the saturated regime. The scatter in \(L_x/L_{bol}\) seen in these diagrams may be attributable to various influences. For instance, previous studies of X-ray activity in other relatively young clusters (e.g., Randich et al. 1996, Figs. 9, 10) indicate that some of the scatter in \(L_x/L_{bol}\) seen for IC 2602 in Figure 6a is due to the range in spectral class covered. In the present study, R21, R83, and R85 are among the earliest spectral range of stars from Table 1 shown in Figure 6. R70 (=W85) was also listed as having a relatively early spectral type (F7; Whiteoak 1961), which would concur with the relatively low level of X-ray activity seen. In addition, in some rare instances the X-ray flux measurements for certain stars may have been slightly underestimated, resulting in an abnormally low \(L_x/L_{bol}\) value. Underestimates of the X-ray flux would occur due to instrumental effects as explicitly discussed in connection with the raster X-ray survey in \(\alpha\) Persei (Randich et al. 1996, § 3.2.1), but which were not addressed during the earlier analysis of the raster X-ray survey in IC 2602 (Randich et al. 1995). Possibly more evident among slow rotators, some stars with slightly higher than usual X-ray activity levels may have been observed during a state of high X-ray emission, such as a flare or postflare state, resulting in overestimates of their normal quiescent X-ray flux levels. Overall, the distribution in X-ray activity as a function of rotation for IC 2602 members compares favorably with similar distributions constructed for other clusters such as the Pleiades and \(\alpha\) Persei: stars with \(v \sin i > 15\) km s\(^{-1}\) or \(P \leq 2\) days exhibiting X-ray activity near or at the saturation level.

The question of magnetic saturation is further complicated by a color dependence of the observed X-ray activity levels. In Figure 6b the distribution is illustrated as a function of Rossby number that yields a somewhat clearer trend with X-ray activity than just the period or color dependence by itself, presumably reflecting the fact that X-ray activity is a function of both. The distribution in Figure 6b is substantially similar to that in Staufer et al. (1997, Fig. 7), but we have used the true rotation periods of the IC 2602 stars rather than the \(v \sin i\) observations in calculating the Rossby number.

One final point deserves to be mentioned: the amplitude of variability does not seem to show any identifiable trend just yet with the X-ray emission. Such a trend might be

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\(^8\) In the traditional picture, \(dJ/dt \propto \Omega^3\) and \(\Omega \propto B\), where \(dJ/dt\), \(\Omega\), and \(B\) represent the angular momentum loss rate, the rotation rate, and the magnetic field of the star, but if this were always true, we would not have rapid rotation.
expected since, as we have shown in Figure 5, there are trends with color and period, and hence with Rossby number. This probably indicates either that this cluster is not old enough for the trend to be obvious or is a result of having an insufficiently large sample. The trend might emerge when the current database has been expanded substantially.

### 3.5. Lithium

Butler et al. (1987) first suggested a connection between Lithium abundance and rotation, showing that four rapidly rotating early-K dwarfs in the Pleiades contained an order of magnitude more lithium than four slow rotators of the same spectral type. Observations by Soderblom et al. (1993) showed unambiguously (using \( v \sin i \) data) that fast rotators in the Pleiades had higher than average lithium abundances than the slow rotators. Jones et al. (1997) show a similar trend in M34 (again using \( v \sin i \) data). Thus, it might be worthwhile to ask about trends in IC 2602.

Randich et al. (1997) have determined lithium abundances for many of the IC 2602 stars. They show that the overall trends of lithium abundance with temperature are similar to those in the Pleiades and \( \alpha \) Per. In addition, they compare the lithium abundances to the \( v \sin i \) observations available (Fig. 12 of Randich et al. 1997). In that figure, the two stars with \( v \sin i \) greater than 30 km s\(^{-1}\) do indeed lie above the trend for the slower rotators. We would like to remove the ambiguities associated with \( v \sin i \) data by replacing them with rotation periods. Figure 7 displays the LTE lithium abundances from Randich et al. (1997) against the \( B-V \) color, marking the stars using their rotation periods (stars without period derivations are marked 99.99). Despite the paucity of the data points (there are several stars with periods but no lithium abundances and vice versa), it is interesting that, indeed, the short-period rotators are located above the mean cluster trend. It might be worthwhile to determine abundances for the remaining unmeasured stars in this cluster and also for those in IC 2391.

### 4. Interpretation Using Stellar Models

One of the goals of the modern study of stellar evolution is to understand the rotational evolution of stars. As soon as new data for individual clusters become available, they offer us a chance to compare the new observations with the current paradigm that may then need to be altered and perhaps even discarded. In the case of IC 2602, we have not found any new data that would necessitate discarding the current paradigm, but the new data appear to clarify several issues and modify one important one. The major results of these data appear to be the delineation of the ultrafast rotators across the \( 0.6 < B-V < 1.6 \) color range, and the identification of several very slow rotators.

The main problem in stellar rotation is to achieve an understanding of the evolution of stellar rotation with age. The important issues concern the internal transport of angular momentum with age, the effects of magnetic saturation, and those of disk interaction. This last effect has assumed an added importance with the discovery of extrasolar planets. A star-disk interaction on the pre-main sequence has been suggested (e.g., Edwards et al. 1993) as the reason for the dichotomy in the observed rotation periods of classical and naked T Tauri Stars. If this were the case, the fast end of the T Tauri distribution should evolve into the fast end of the distributions for young open clusters and the slower T Tauri stars should evolve into the slower rotators in young clusters, with reasonable disk-interaction timescales. Alternatively, one could reverse the argument and use the observed slow rotators in young open clusters to derive disk-interaction timescales.

We will not discuss details of the various theoretical models here, preferring to present them elsewhere (Barnes et al. 1999; Barnes 1998), but we will compare one set of models to the observations presented here. The rotation periods of the IC 2602 stars from Table 1 and those of their twin cluster IC 2391 (Patten & Simon 1996) are plotted in Figure 8 against \( B-V \) color. We have also overlotted a number of “isoarchs” taken from Barnes (1998) each of which represents the locus of points with different stellar mass but the same initial conditions. The lowest of these corresponds to stellar models of masses 1.2, 1.0, 0.8, and 0.6 \( M_\odot \) that were started off with 4 day initial periods and had no disk interaction. The next one consists of the same models but with a 16 day initial period. The ones above all have initial periods of 16 days, but have been disk locked for successively longer times ranging from 0.3 to 10 Myr. If the models are correct, then the observations of the ultrafast rotators in these clusters are consistent with 4 day initial periods and no disk locking whatsoever.

The behavior of the slow rotators is more surprising. Most of them lie above (i.e., they are slower than) the isoarch with 16 day starting period and no disk locking. Thus, the models predict a very narrow range of rotation periods for stars without disks regardless of the initial period. Since the majority of the observations lie above the isoarch for a 16 day initial period and no disk locking, the conclusion seems to be inescapable that the majority of stars in these open clusters, and perhaps all open clusters, have been disk locked for significant periods of time. Although one of the slow rotators is the problematic star B134 (which has been designated as a photometric binary), there are some other very slow rotators and the models seem to require disk lifetimes up to 10 Myr to explain them.
Rotation periods of stars in IC 2391 (open circles) and IC 2602 (filled circles) with theoretical models from Barnes (1998) overplotted. The initial periods and disk lifetimes for the models are indicated on the right. The models suggest that disk interaction is the norm rather than the exception.

The majority, at least in the 1.2 to 0.6 $M/M_\odot$ range under consideration here, seem to be explainable with disk lifetimes up to 5 Myr. With these data alone, we cannot say whether any particular disk lifetime is preferred as there does not seem to be a concentration about any particular isoarch.

5. CONCLUSIONS

We have monitored 33 late-type stars in the 30 Myr old open cluster IC 2602 for photometric variability due to spot modulation. Rotation periods were derived for 29 of these stars (including three for which only $v \sin i$ upper limits existed before). The rotation periods derived ranges from 0.2 to 10 days, representing the entire range from the ultrafast rotators to the slowest rotators yet discovered in a cluster of this age.

We find rapid rotation across the entire $0.5 < B-V < 1.6$ color range. The existence of rapid rotation may be interpreted as evidence of magnetic saturation, since theoretical models of rotating stars cannot create ultrafast rotators otherwise. Although the IC 2602 sample here covers a somewhat limited mass range, the uniformity of the color dependence may possibly be interpreted as evidence for a mass-dependent saturation threshold.

The range of rotation periods observed at any color in this cluster is so wide that theoretical models of angular momentum loss are unable to explain their existence without some additional effect, such as a star-disk interaction leading to rotational slowdown. If the theoretical models are correct, then the majority of the IC 2391 and IC 2602 stars have experienced significant disk locking (of the order of Myr) on the pre-main sequence.

The amplitude of variability of individual stars displays trends with both color and rotation period. Bluer stars have smaller variability amplitudes, as do stars with rotation periods longer than 6 days. These behaviors might help in understanding the selection effects of the presently available rotation period data and in planning future observations.

Overall, the distribution in X-ray activity as a function of rotation for IC 2602 members compares favorably with similar distributions constructed for other clusters such as the Pleiades and $\alpha$ Persei: stars with $v \sin i > 15$ km s$^{-1}$ or $P \leq 2$ days exhibiting X-ray activity near or at the saturation level. The weak trend between X-ray activity level and Rossby number previously noted for this and other clusters (Stauffer et al. 1997; Patten & Simon 1996) continues to hold.

Lastly, we have compared our period determinations with the lithium abundance determinations of Randich et al. (1997). The small size of the sample precludes definitive statements but the shorter period stars seem to display elevated lithium abundances relative to slower rotators of the same color.

Part of this work was completed while S. B. held the Lowell Fellowship, funded by the BF Foundation, at Lowell Observatory. S. B. would also like to thank Robert Zinn for his support, Jerry Orosz and Eric Rubenstein for their generous help with all aspects of the observation and reduction of these data, and Yasuhiro Hashimoto for help with IDL. C. F. P. and J. R. S. acknowledge support for this research from NASA grants NAGW-2698 and NAGW-3690. The assistance and support of the CTIO staff and personnel are gratefully acknowledged in contributing to the successful undertaking of the observations.

APPENDIX

COMMENTS ON INDIVIDUAL STARS

B134.—This star is a photometric binary.

W79.—The approximately 6 day variability is visible directly in the raw light curve, which also suggests some spot evolution.

R15.—Provisional period with smallest amplitude of variability. Secondary spike chosen in spectrum. Stellingwerf analysis also gives most power at 3.6 days.
No suitable comparison stars were available in images, preventing analysis.

Structure in the phased light curve suggests two major spot groups. Shape of light curve remains the same even if C. P.'s data are ignored.

5–6 day variability obvious from the raw light curve.

Provisional period. Owing to possible phase shifting in data over the combined data set, the plotted light curve shows only S. B.'s data. We suspect two major spot groups on this star.

Messy light curve. Excising various segments of the data does not reduce the scatter. Variability is apparent from the raw light curve. Period of 2.21 days is essentially the same as the previously known period (Patten et al. 1996).

Messy light curve. Excising various segments of the data reduces the scatter but produces a less convincing phased curve. Half-day variability is apparent from the raw light curve itself. Amplitude of variability is small.

The 4 day period is believable despite being a multiple of a day. Variability is large and unmistakable in the raw light curve. The 4 day periodicity results in a light curve with missing phase coverage.

No strong peak is visible in periodogram based on 92 combined observations. Using 46 observations in the Prosser data for this star, C. P. finds a suggestive period at \( P \approx 0.8 \) days = 19 hr, with an amplitude of \( \Delta V = 0.04 \) mag.

We confirm the previous period of 0.78 days (Patten et al. 1996; C. F. Prosser 1997, private communication).

The highest power is visible at twice the chosen frequency, but the correct period can be picked up by inspection of the raw light curve that shows the 5–6 day variability clearly.

Period derived here confirms the previously suspected 6.4 day period (Patten et al. 1996).

The previously derived period (Patten et al. 1996) is confirmed.

Phased light curve shows substructure similar to that displayed by other rapid rotators, possibly because the spot pattern changed during the run.

The approximately 4 day periodicity is apparent from the raw light curve and appears in all three parts of the observing run. The phased light curve is a little noisy. Phase change between S. B.'s data and C. P.'s gives the appearance of two superposed light curves. Only S. B.'s data is displayed in Figure 3.

Significant detection in periodogram, although period error approaches \( \sim 1 \) day for this star due to more limited coverage for this long period.

The same periodicity of \( \sim 0.57 \) days persists in various subsets of the data. The light curve appearance using all observations is somewhat degraded due to small changes in phase between data subsets. This may be interpreted as evidence of differential rotation or migration of starspots. Amplitude of variability is \( \sim 0.02 \) mag in S. B.'s data, increasing to \( \sim 0.055 \) in C. P.'s observations.

Variability is apparent in the raw light curve. However, the behavior of the star changed in the second half of the run, resulting in a good phased light curve once these data are deleted.

Strong aliasing effects prevent specific period determination for this star. Based on a subsample of 30 observations and observed \( v \sin i \) for R68, C. P. indicates a suggestive period at \( P \approx 0.66 \) days \( \sim 16 \) hr, with amplitude \( \Delta V = 0.04 \) mag. Previous work (Patten et al. 1996) suggests a provisional 0.99 day period.

The variability is apparent from the light curve but the phased light curve does not look as good as would be expected, probably because of the small amplitude of variability.

The spectrum is double-peaked, likely due to the star's change in behavior during the run. The star is systematically brighter in C. P.'s data set.

Variation occurs in light curve appearance between S. B./C. P.'s data sets; only S. B.'s data are displayed in the phased curve. Formal period error is on order of 1 day.

Phased light curve shows S. B.'s data set.

No period determination. Variation approaching 0.1 mag seen in C. P.'s data, however.

This is the fastest rotator. We confirm the previously derived period (Patten et al. 1996; C. F. Prosser 1997, private communication).

The 4.8 day period found here is slightly different from the previously estimated period of 4.47 day (Patten et al. 1996; C. F. Prosser 1997, private communication).

Provisional period. The raw light curve seems to show some 2 day periodicity. Phase coverage is not good because the period is a multiple of a day. Photometric binary?

Some points (not all in the same data set) are off the sequence on the phased light curve, indicating irregular variations superposed on the rotational modulation.

This star has a nearby companion as indicated in Randich et al. (1995). Available photometry suggests a photometric binary in \( V - I \).

The first week's data lies above the phased sequence so the light curve looks better without it. The previous period from Patten et al. (1996) is confirmed.

Periodicity under 2 days is apparent from the raw light curve. Previously known to have a similar period (Patten et al. 1996; C. F. Prosser 1997, private communication).

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