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ADDITIONAL PERIODIC VARIABLES IN NGC 2264

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ABSTRACT

We present results from a second season of monitoring fields in the young cluster NGC 2264 at Van Vleck Observatory. In Paper I of this series, we reported the discovery of nine periodic variables—all interpreted as spotted pre–main-sequence stars. That has now been increased to 31, one of which is quite unusual. The preliminary result reported in Paper I—that the frequency distribution of rotation periods in NGC 2264 is significantly different from what is seen in the Orion Nebula cluster (ONC)—is confirmed. In particular, the distribution peaks at a period of about 4 days, precisely where there is a gap in the ONC distribution. There is also a good number of very rapidly rotating stars and a long tail of slow rotators. The distribution can be understood, at least qualitatively, in terms of a disk-locking model of rotational evolution. In this interpretation, the majority of stars in NGC 2264 must have unlocked from their disks by an age of about 1 million years, and spun up roughly in accordance with conservation of angular momentum. A minority (about 20%) are conserving angular velocity instead (i.e., locked to their disks). The unusual star, 15D, has an apparent period of about 48 days and a light curve indicative of an eclipse by a nonstellar object. Its amplitude exceeds 3 mag. Our fragmentary data suggest a complex structure for the eclipsing body. It could be a feature (protoplanet?) in this star's circumstellar disk and, as such, deserves observational attention.

Key words: open clusters and associations: individual (NGC 2264) — stars: pre–main-sequence — stars: rotation — stars: spots

1. INTRODUCTION

In 1995–1996 we began monitoring four fields in the young cluster NGC 2264 with a CCD attached to the 0.6 m telescope at Van Vleck Observatory, on the campus of Wesleyan University. The goal was to determine rotation periods for stars by finding the periodic modulation of their brightness caused by starspots (both cooler and hotter than the photosphere). A similar program for the Orion Nebula cluster (ONC) has been running successfully for many years (see, e.g., Choi & Herbst 1996 and references therein). In the ONC, we discovered that the rotation period distribution is bimodal, with a short-period peak near 2.5 days and a long-period peak near 8 days. Since NGC 2264 is believed to be a somewhat older cluster than the ONC (at least the central parts of the ONC), it serves as an interesting and important extension of the work. The most likely explanation of the bimodal distribution is that disks act to slow the rotation of pre–main-sequence (PMS) stars and create a rotational barrier at around a 7 or 8 day period for a typical ONC PMS star. NGC 2264 promises to tell us what happens next. Do most stars lose their disks on timescales of the age of an ONC star (i.e., ~ 1 Myr) and spin up in accordance with angular momentum conservation? Or do disks persist for the longer times typical of the age of an NGC 2264 member (between 1 and 15 Myr; Makidon et al. 1996)? Results of the first season of observation were reported by Kearns et al. (1997, hereafter Paper I), and include the first detections of rotation periods for stars in that cluster. Here we report results from the 1996–1997 season. Because of better time coverage, we were able to significantly increase the number of rotation periods found—from nine to 31. Additional motivation and background for this study were given in Paper I and need not be repeated here.

2. PERIODIC VARIABLES

The photometric data are obtained in the Cousins *I* band with the 0.6 m Perkin Telescope of Van Vleck Observatory. The observational techniques and data reduction techniques are identical to those reported in Paper I and references therein. An interesting aspect of this season's data is that our time coverage was better than normal, owing to good luck with weather and equipment, and dedicated observers. The fields monitored are identical to those shown in Paper I, and are denoted A, B, C, and D. Identification charts and positions of the field centers may be found in Paper I. The *I* magnitudes are unknown, since we have only differential photometry; however, we estimate the limiting magnitude to be about 16 in *I*, and most detected periodic variables are at least 1 or 2 mag brighter than the limit. The time coverage achieved this season is shown in Figure 1.

Our technique is to perform photometry on all stars on each frame, each night using standard IRAF packages. We use a bootstrap method described in earlier papers in this series to identify a set of comparison stars. In this case, we used four to six such stars in each field (see Table 1). The reference magnitude on each frame is established as the average of these magnitudes. Differential magnitudes relative to the reference level are computed and form our time series. The periodogram technique of Scargle (1982; see also Horne & Baliunas 1986) is employed to search for periodicities. Estimation of false-alarm probabilities (FAPs) is an important and difficult part of this process. Since the data sets are not sampled uniformly in time, there is no definitive method to estimate the FAP. We, therefore, use a Monte Carlo simulation of the data that employs two sources of scatter—"night to night" and "within a night" (see Paper I). In the real data, the night-to-night scatter is commonly larger, because of real variations on timescales of 1 day or longer. Monte Carlo simulations that do not account for this yield very small FAPs, even for randomly generated data sets. Failure to recognize this effect can lead to claims of large numbers of periodicities for stars that, in fact, have only random variation.

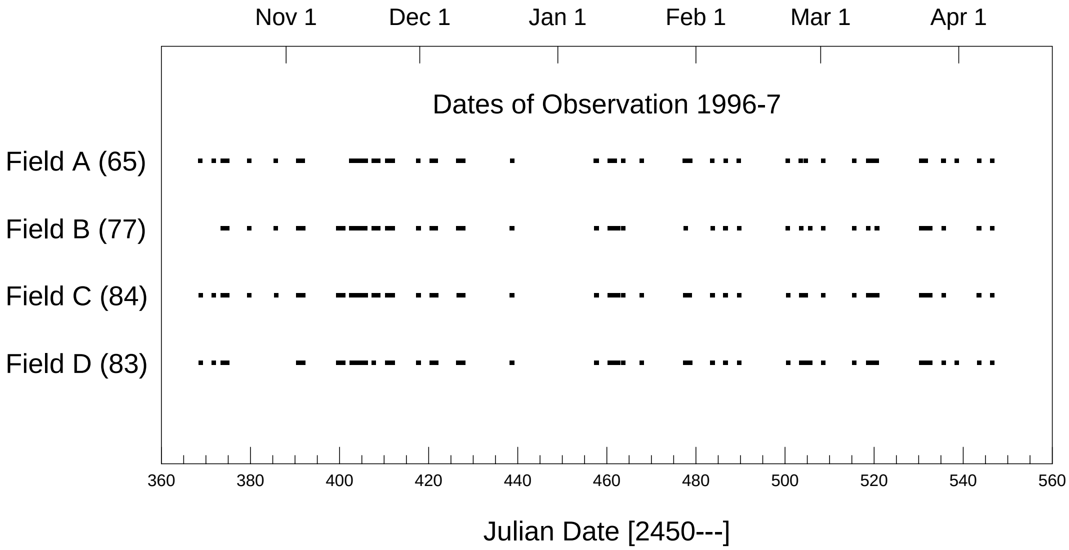

FIG. 1.—Times of observations for each of the four fields. The total number of observations in each field is given in parentheses on the axis label.

Two examples of periodograms are shown in Figure 2. These are the stars with the highest power and lowest power among those designated as periodic. Note that stars with periodicities always show multiple peaks in our periodograms, owing to the sampling frequency (of nearly 1 day), which "beats" with the true period to create aliases. In fact, the periodogram between 0.5 and 1.0 day^{-1} is an almost perfect reflection of the portion between 0 and 0.5 day^{-1}, owing to this phenomenon. Additional reflections, of course, occur at higher frequencies. Separating true periods from aliases is a second difficulty in this work, which is addressed below. The Monte Carlo simulations establish a power level at which the FAP is 0.01. All of the stars that exceed this level are listed in Table 2, along with a few stars slightly below the level whose periods confirm those reported in Paper I. The normalized power as defined by Horne & Baliunas (1986) is given, along with the period, and a possible alias if we are not certain of the true period. In all, we identify 31 stars that are periodic at a high (roughly 99%) confidence level.

It is gratifying to note that every star identified as periodic in Paper I was rediscovered as periodic this season. As shown in Table 2, the periods are also identical to within the errors. The same thing is found for the ONC, as discussed by Choi & Herbst (1996). The stability of the periods supports our claim that we are measuring rotation periods, and validates, to some extent, our method of assessing FAPs. In Paper I we also identified four stars that had "possible" periods. One of these was found again with an identical period, and is therefore listed in Table 2. The other three were not recovered, and are dropped from consideration in this paper.

Light curves for the newly discovered periodic variables are shown in Figures 3 and 4. For ease of presentation, we have divided the stars into larger amplitude variables (Fig. 3) and smaller amplitude variables (Fig. 4). There is no difference in the variability mechanism, which we assume to be

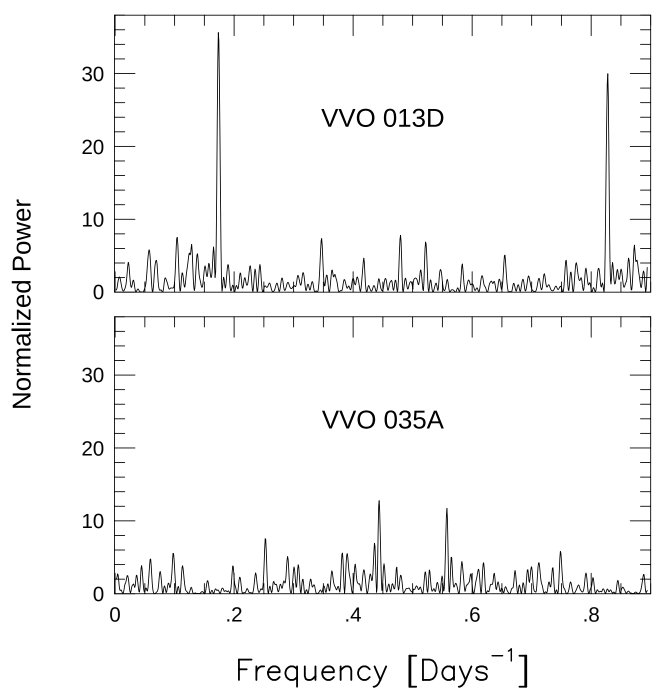

FIG. 2.—Periodograms of two stars with the most (*top*) and least (*bottom*) significant peaks exceeding the 1% confidence limits.

TABLE 1

COMPARISON STARS

Star	σ	Star	σ	Star	σ	Star	σ
1A	0.019	19B	0.010	2C	0.017	17D	0.022
3A	0.016	22B	0.010	4C	0.011	21D	0.028
15A	0.016	45B	0.018	6C	0.020	27D	0.021
22A	0.016	49B	0.025	33C	0.012	39D	0.019
29A	0.015	55B	0.020			40D	0.024
30A	0.018						

TABLE 2
PERIODIC VARIABLES WITH FAP ≤ 0.01

Star	Period 1996–1997 (days)	Power	Period 1995–1996 (days)	Alias
4A	1.31	17.2	...	4.20
8A	4.68	19.3	...	...
12A	10.86	18.2	...	...
17A	12.63	23.2	...	...
26A	8.95	20.8	8.95	...
27A	3.77	13.3	...	...
28A	9.88	20.8	...	...
35A	2.25	12.9	...	...
1B	4.30	25.2	...	...
20B	16.49	31.2	...	...
26B	4.47	15.2	...	...
31B	4.74[a]	12.1	4.71	...
51B	4.62	28.0	4.60	0.82
1C	5.97	21.8	...	...
23C	7.52	20.3	...	...
25C	4.24	25.4	...	...
26C	1.96[a]	10.5	1.97	2.03
28C	3.34	25.6	3.33	1.42
41C	1.21	21.8	1.20	5.83
1D	2.92	18.1	...	...
9D	3.15[a]	15.2	3.16	1.46
13D	5.76	35.8	5.75	1.21
15D	47.09	20.7	...	...
16D	2.69[a]	12.4	2.69[a]	...
22D	5.18	22.7	...	...
24D	2.93	21.7	...	...
25D	9.61[a]	18.3	9.70	0.91
31D	4.44	17.0	...	...
37D	1.27	18.0	...	...
44D	1.76	25.3	...	...
50D	3.62	27.4	...	...

[a] "Probable" period, with power equivalent to FAP ≳ 1%.

spots on a rotating star, between these sets. The only anomalous object is 15D, which is discussed further below. The light curves found are representative of spotted variables in their amplitudes, shapes, and periods. We use lines in these figures to connect data points obtained on the same night. Because the periods are larger than 1 day and the sampling interval on a night is at most a few hours, data connected by lines were obtained in a single cycle. Plots like this usually allow one to easily distinguish between the true period and a beat period. Occasionally the distinction between true period and alias is less obvious; in such cases, we report both periods in Table 2. The most likely periods are used in forming the histogram below.

3. DISTRIBUTION OF ROTATION PERIODS

In Figure 5, we show the distribution of rotation periods in NGC 2264 and compare it with the results of our similar studies in the ONC. The top panel shows results for the Trapezium cluster, which is the central portion of the ONC and arguably its youngest part (Hillenbrand 1997). Comparing with Paper I, it may be seen that as the sample size has increased in NGC 2264, the basic distribution has not changed. The bulk of the stars rotate with periods around 4 days or shorter. This is in contrast to the ONC, where 4 days is a gap between the peaks. A Kolmogorov-Smirnov double-sided test (Press et al. 1986, p. 472) indicates that the probability that the ONC (including the Trapezium) and NGC 2264 samples are drawn from the same parent population is only 10^{-3}, confirming the qualitative impression of significantly different distributions.

As discussed in Paper I, the differences between the ONC and NGC 2264 can be understood in terms of a simple

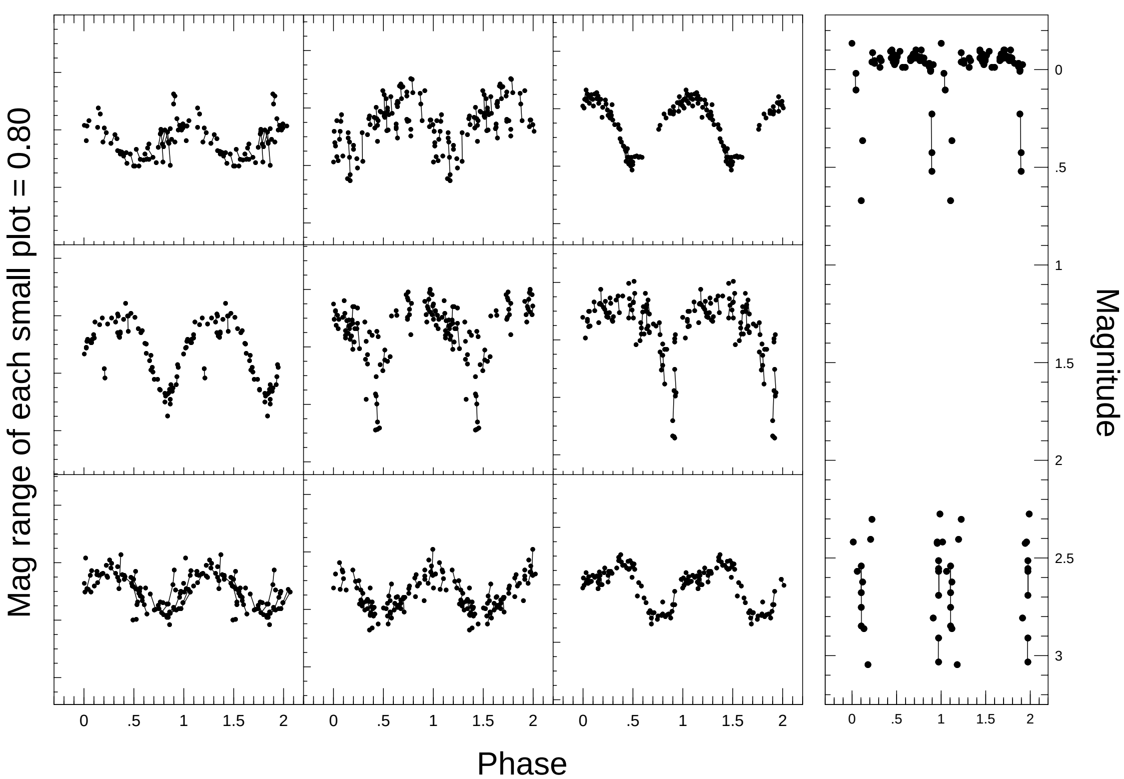

FIG. 3.—Light curves folded with the appropriate period for stars with relatively large amplitudes. Lines connect observations obtained on the same nights. The one star in the panel at right is 15D (see § 4). The nine other stars are, from left to right: *top row*, 1D, 12A, 13D; *middle row*, 17A, 22D, 23C; *bottom row*, 44D, 50D, 51B.

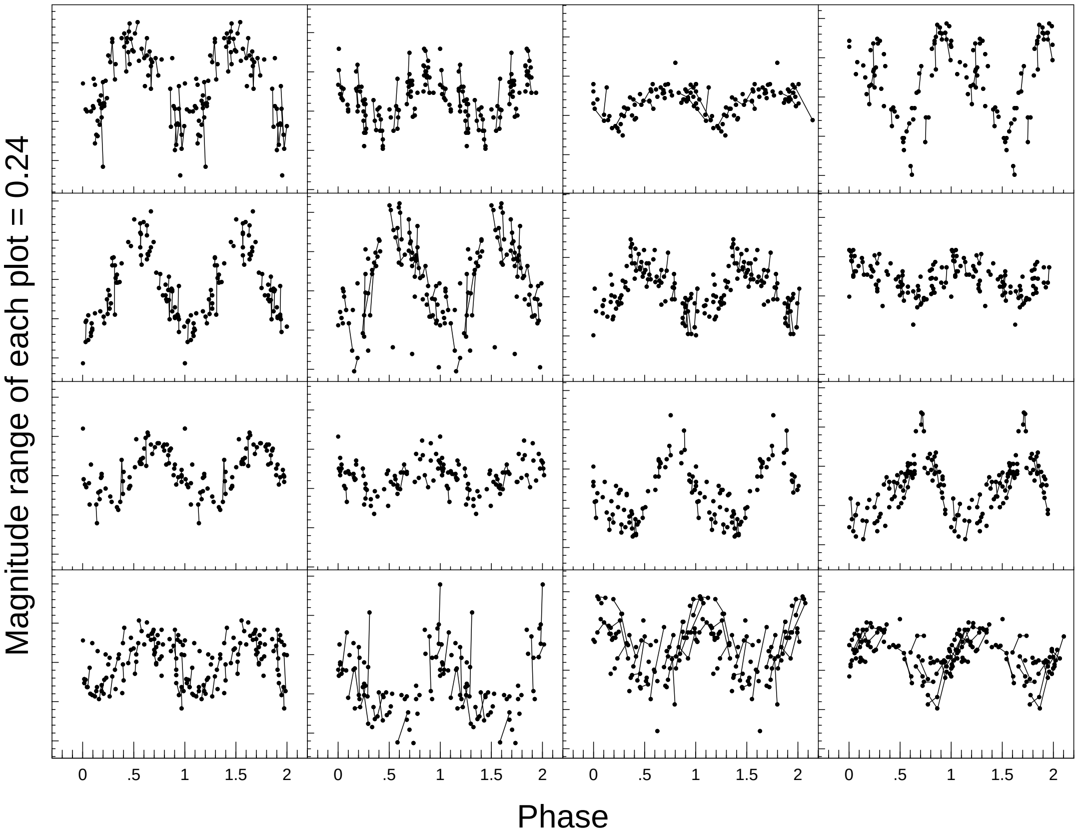

FIG. 4.—Light curves folded with the appropriate period for stars with relatively small amplitudes. The star identifications are, from left to right: *top row*, 1B, 1C, 4A, 8A; *second row*, 20B, 24D, 25C, 26B; *third row*, 26A, 27A, 28A, 28C; *bottom row*, 31D, 35A, 37D, 41C.

model of rotational evolution: namely, conservation of angular momentum during Hayashi phase contraction. It may be shown that $P \propto t^{-2/3}$ under these conditions. If NGC 2264 were about 3 times older than the ONC, the 8 day period peak in the ONC would translate to a 4 day peak in NGC 2264, as observed. This implies that *most* of the stars in the ONC have decoupled from their disks. There is a set of stars in NGC 2264 that are spinning quite slowly, however. Two explanations appear possible. Either some stars do not lose their disks for more than 3 Myr, or there is an age range within the cluster and the younger stars spin slower. Our data alone cannot decide between these possibilities. Our conclusion is that if the ONC and NGC 2264 can be compared (i.e., all other factors being equal) and form a basis for generalization, then the data suggest that disks will typically act as rotational brakes for only the first couple of million years. By a cluster age of about 3 Myr, only a minority of stars ($\sim$20%) apparently continue to interact with their disks. If the disk-unlocking process can be described as an exponential decay, the numbers quoted above suggest an *e*-folding time of about 2 Myr, which is relatively short compared with values sometimes adopted in rotational modeling (e.g., Bouvier, Forestini, & Allain 1997). It should, of course, be kept in mind that our results refer to clusters. Certainly it is possible that disk survival times and locking times are longer in associations such as Taurus.

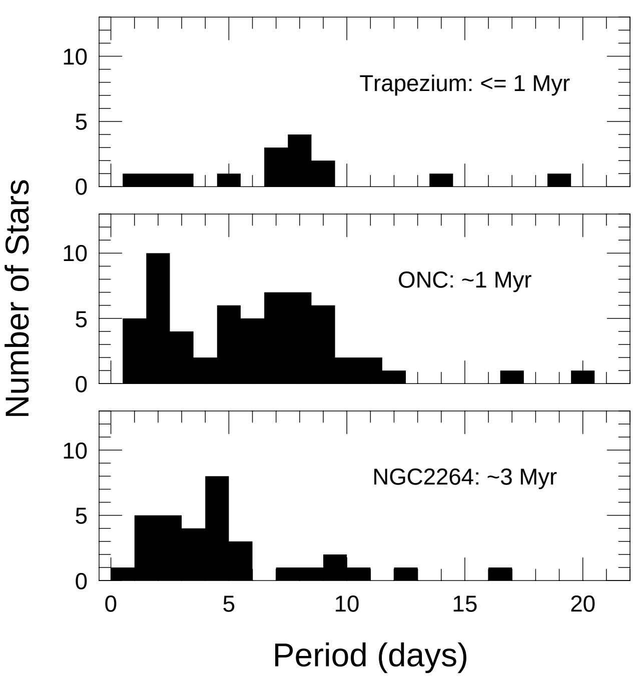

FIG. 5.—Histograms of rotation periods in the ONC from Herbst (1998) and in NGC 2264. The ONC data are divided into a younger portion—the Trapezium cluster—and the rest, following Hillenbrand (1997).

Additional comments and caveats presented in Paper I apply to the above discussion as well. One is quite important, and we repeat it here: namely, our evolutionary interpretation depends on the assumption that the masses of the stars we are comparing in the ONC and in NGC 2264 are the same. In the ONC, the masses of periodic stars span a wide range, from about 2 $M_\odot$ to about 0.5 $M_\odot$. There is a weak indication in the ONC that rotation period increases as mass decreases. If the periodic NGC 2264 stars were

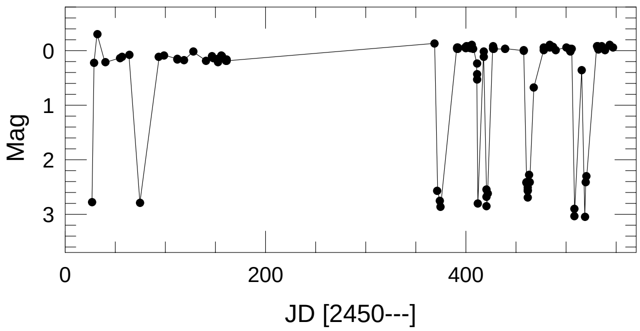

FIG. 6.—Light curve of 15D over two seasons

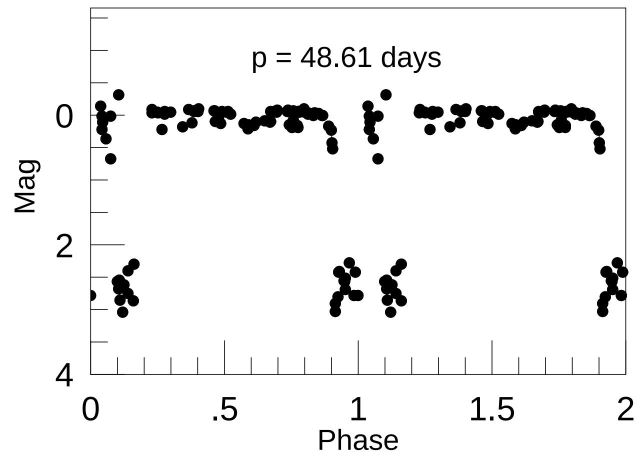

FIG. 7.—Light curve of 15D over two seasons, folded with a period of 48.61 days.

systematically more massive than their ONC counterparts and if the trend just mentioned is real, it could perhaps account for the differences in rotation observed between the clusters. The few spectral types we have and crude magnitudes, as well as the absence of a strong mass effect in ONC, argue against this interpretation at present, but a more definitive statement must await better knowledge of the colors, magnitudes, and spectral types of the NGC 2264 stars.

4. THE UNUSUAL STAR 15D

During the first season of observation, 15D was noted as a large-amplitude irregular variable based on two data points that were more than 3 mag below its typical brightness. Irregular variables with such large amplitudes are rare, but not unknown, in young clusters. What is unusual about this star is that its variations appear to be periodic. In Figure 6, we show the light curve of 15D over two seasons. The deep minima recur with a period of about 48 days. The abrupt change in brightness level and the nearly constant brightness between minima is also unlike the typical irregular variable found in star-forming regions; it strongly suggests occultation of the star by some foreground object. If the minima are strictly periodic, then the data furthermore suggest that the occulting object is in orbit about the star. The period is 48–49 days, based on the six cycles observed. We were able to predict, on the basis of these data, the occurrence of another eclipse in 1997 September and in 1997 November, and these eclipses were detected in the raw data.

A folded light curve based on the first two seasons of data is shown in Figure 7. An outstanding feature is the bright peak in the center of the eclipse. The phenomeon is seen independently during two of the events, so if this object is truly periodic, there is no doubt about the bright phase near what should have been the center of minimum. The width of the eclipse, its depth, and the central bright portion all indicate that the occulting body cannot be a star. If it is orbiting the primary, then it may be a protostar or protoplanet, or some feature in the circumstellar disk. The central bright portion suggests that its shape is that of a torus. Further speculation is unwarranted at this time. We simply note that the star deserves additional observational attention. We have cooperated with M. Ibraghimov of Maidanak Observatory, in the Republic of Uzbekistan, to obtain well-sampled light curves of this star during the early part of the 1997–1998 season, and these will be reported if successful. If further observations confirm the periodic nature of this variable, it could be a unique and important star for studies of disk evolution and, possibly, planetary formation.

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