

## ROTATIONAL PERIODS OF VERY YOUNG BROWN DWARFS AND VERY LOW MASS STARS IN CHAMAELEON I<sup>1</sup>

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### ABSTRACT

We have studied the photometric variability of very young brown dwarfs and very low mass stars (masses well below  $0.2 M_{\odot}$ ) in the Cha I star-forming region. We have determined photometric periods in the Gunn  $i$  and  $R$  bands for the three M6.5–M7 type brown dwarf candidates Cha H $\alpha$  2, Cha H $\alpha$  3, and Cha H $\alpha$  6 of 2.2–3.4 days. These are the longest photometric periods found for any brown dwarf so far. If interpreted as rotationally induced, they correspond to moderately fast rotational velocities, which is fully consistent with their  $v \sin i$  values and their relatively large radii. We have also determined periods for the two M5–M5.5 type very low mass stars B34 and CHXR 78C. In addition to the Gunn  $i$ - and  $R$ -band data, we have analyzed  $JHK_S$  monitoring data of the targets, which have been taken a few weeks earlier and confirm the periods found in the optical data. Upper limits for the errors in the period determination are between 2 and 9 hr. The observed periodic variations of the brown dwarf candidates as well as of the T Tauri stars are interpreted as modulation of the flux at the rotation period by magnetically driven surface features, on the basis of a consistency with  $v \sin i$  values as well as  $R-i$  color variations typical for spots. Furthermore, the temperatures even for the brown dwarfs in the sample are relatively high ( $>2800$  K) because the objects are very young. Therefore, the atmospheric gas should be sufficiently ionized for the formation of spots on one hand, and the temperatures are too high for significant dust condensation and hence variabilities due to clouds on the other hand. A comparison with rotational properties of older brown dwarfs shows that most of the acceleration of brown dwarfs takes place within the first 30 Myr or less. If magnetic braking plays a role, this suggests that the disk dissipation for brown dwarfs occurs between a few and 36 Myr.

*Subject headings:* stars: activity — stars: fundamental parameters —  
stars: individual (Chamaeleon H $\alpha$  1, Chamaeleon H $\alpha$  2, Chamaeleon H $\alpha$  3,  
Chamaeleon H $\alpha$  4, Chamaeleon H $\alpha$  5, Chamaeleon H $\alpha$  6, Chamaeleon H $\alpha$  7,  
Chamaeleon H $\alpha$  8, Chamaeleon H $\alpha$  9, Chamaeleon H $\alpha$  10, Chamaeleon H $\alpha$  11,  
Chamaeleon H $\alpha$  12, B34, CHXR 73, CHXR 78C) — stars: late-type —  
stars: low-mass, brown dwarfs — stars: rotation

### 1. INTRODUCTION

A photometric monitoring campaign of bona fide and candidate brown dwarfs in the Cha I star-forming cloud has been carried out in two filters in order to study the time dependence of their brightness and color. It is known that magnetically driven surface features (spots) of stars modulate the brightness of the star as it rotates (e.g., Bouvier et al. 1993 and references therein). The presented photometric observations of brown dwarfs are aimed at the study of such spot-driven variabilities in the substellar regime in order to test if brown dwarfs have magnetic spots. Furthermore, since surface features modulate the emitted flux *at the rotational period*, the photometric study is aimed at the determination of rotational periods for brown dwarfs.

Rotational periods are fundamental (sub)stellar properties. The knowledge of rotational periods for objects

covering a wide range of ages is important for the understanding of the evolution of angular momentum. In addition, scanning the period-age diagram observationally for brown dwarfs with ages of less than 100 Myr provides a test of substellar evolutionary theories since the onset of deuterium burning is expected to have an observable effect on the angular momentum evolution. The contraction of brown dwarfs is expected to be temporarily decelerated or even stopped in the first several million years of their lifetime owing to the ignition of deuterium (e.g., Burrows et al. 2001). However, since age estimates are also often model-dependent, the significance of such a test might be somewhat limited. Furthermore, rotation rates are critical parameters for rotationally induced phenomena, like dynamo activity (supposed to cause surface spots) and meteorological processes.

For solar-type main-sequence stars there is a correlation between rotation and activity: the faster the rotation the more active the star is, measured in terms of chromospheric H $\alpha$  and Ca II emission, flare activity, as well as coronal X-ray emission. There are indications that this relation becomes invalid for later spectral types (late M) and lower masses. In particular, near and below the substellar limit several rapid rotators are found with no or very little signs of chromospheric activity (e.g., Basri & Marcy 1995; Delfosse et al. 1998; Gizis et al. 2000).

For very young stars on the pre-main sequence (T Tauri stars) the relation between activity and rotation is still a

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matter of debate: correlations between rotation and X-ray emission have been found for T Tauri stars in Taurus (Bouvier 1990; Neuhäuser et al. 1995; Stelzer & Neuhäuser 2001), whereas a recent publication by Feigelson et al. (2002) reports the absence of a connection between X-ray emission and rotation for a large sample of T Tauri stars in Orion.  $H\alpha$  emission, on the other hand, is not a definite activity indicator for very young objects, because they often have circumstellar accretion disks, which are significant additional  $H\alpha$  emission sources. A study of the rotation-activity relation in the substellar regime at this very young age is hampered up to now by the lack of observational constraints of rotation parameters:  $v \sin i$  values are known for two very young brown dwarfs and 12 brown dwarf candidates (Joergens & Guenther 2001; White & Basri 2003). Furthermore, Bailer-Jones & Mundt (2001) found photometric periods for two very young late-M dwarfs in  $\sigma$  Ori, which might be rotational periods.

For very cool objects (spectral type late M, L) surface spots might not play a significant role, but another important process may affect the time dependence of the observed flux of the objects: below a temperature of about 2800 K the condensation of dust sets in (e.g., Tsuji, Ohnaka, & Aoki 1996a, 1996b; Allard et al. 1997; Burrows & Sharp 1999). Inhomogeneities in dust cloud coverages may cause observable photometric variations.

In spite of the demonstrated significance of rotational periods, the number of brown dwarfs with known rotational periods is rather small (see § 2). This is particularly the case at very young ages. We have therefore carried out a photometric monitoring campaign of brown dwarfs and very low mass stars in the Cha I star-forming cloud and determined periods for three brown dwarf candidates. The targets are introduced in § 3; the data acquisition and analysis is described in §§ 4 and 5. The results are presented in § 6 and discussed in § 7, followed by a summary in § 8.

## 2. HITHERTO KNOWN PERIODS FOR BROWN DWARFS

Several studies of the photometric behavior of late-M and L dwarfs have been carried out so far. They have led to the detections of a handful of brown dwarfs showing periodic variabilities and of many, mostly substellar L dwarfs, showing nonperiodic variabilities. We compiled all photometric periods that we have found for brown dwarfs in the literature in Table 1 and ordered them by increasing age.

The nature of the detected periodic variations are not finally clarified. Tinney & Tolley (1999) report variations of an M9 dwarf in narrowband filters, which are sensitive to changes in TiO absorption features and therefore to clouds.

Bailer-Jones & Mundt (2001) detected significant periods below 1 day for four late-M and L dwarfs, among them the very young object S Ori 31. Furthermore, they have found hints for a period for S Ori 33. Out of these five periods, four might be rotational periods according to the authors. The detected periods below 1 day for S Ori 31 and S Ori 33 imply very rapid rotational velocities on the order of  $100 \text{ km s}^{-1}$  (see § 7.3) if confirmed as rotational periods. Furthermore, they find nonperiodic variations for several L dwarfs with timescales of hours and suggest that one sees the formation and dissipation of clouds rather than rotationally driven features. Martín, Zapatero Osorio, & Lehto (2001) report a varying periodicity found in  $I$ -band photometry of the M9.5 dwarf BRI 0021–0214. The authors suggest that the variations are caused by inhomogeneous clouds rather than spots because the object is very inactive in terms of  $H\alpha$  and X-ray emission despite a very fast rotation. Clarke et al. (2002) found periodic variations of the brightness of Kelu 1. The detected period of 1.8 hr is consistent with the rotational velocity. Nevertheless, Clarke & Tinney (2002) found no evidence for variability in dust-sensitive molecular lines, and the nature of the variations remains still unclear. Recently,

TABLE 1  
PHOTOMETRIC PERIODS OF BROWN DWARFS FROM THE LITERATURE

Object	Age	Mass ( $M_{\odot}$ )	SpT	Period (hr)	Amplitude (mag)	Reference
S Ori 31 .....	1–5 Myr	...	(M6.5)	7.5	0.012	1
S Ori 33 .....	1–5 Myr	...	(M6.5)	8.6, 6.5	0.010	1
CFHT-PL 8 .....	100–120 Myr	0.08	...	9.6	0.028	2
LP 944-20 .....	475–650 Myr	0.06	M9	...	0.04*	3
BRI 0021–0214 .....	$\geq 1$ Gyr	...	M9.5	19.2, 4.8	0.018, 0.007	4
2M1334 .....	$\geq 1$ Gyr	...	L1.5	2.7, 6.3, 1.0	0.020	1
Kelu 1 .....	$\geq 1$ Gyr	$< 0.07$	L2	1.8	0.012*	5
2M1146 .....	$\geq 1$ Gyr	...	L3	5.1	0.015	1
SDSS 0539 .....	$\geq 1$ Gyr	...	L5	13.3	0.011	1
2MASS 0746+20AB .....	$\geq 1$ Gyr	...	L0.5	31.0	0.010	6
2MASS 1300+19 .....	$\geq 1$ Gyr	...	L1	238.	0.015	6

NOTES.—S Ori 31, S Ori 33, and CFHT-PL 8 are eventually stars but have been included because of their closeness to the hydrogen-burning mass limit. Masses are estimates. Ages of the field brown dwarfs BRI 0021–0214 to 2MASS1300 are unknown but supposed to be on the order of 1 Gyr or more. The spectral types of S Ori 31 and S Ori 33 are estimates. Amplitudes are measured in broadband  $I$  filters, except for the ones marked with an asterisk; these refer to narrowband observations (see references for details). Some object names are acronyms as given by the authors; their full names are as follows: S Ori 31 = S Ori J053820.8–024613; S Ori 33 = S Ori J053657.9–023522; CFHT-PL 8 = VLC J0342268+245021; 2M1334 = 2MASSW J1334062+194034; 2M1146 = 2MASSW J1146345+223053; SDSS 0539 = SDSSp J053951.99–005902.0; 2MASS 0746+20AB = 2MASSI J0746425+200032; 2MASS 1300+19 = 2MASSW J1300425+191235.

REFERENCES.—(1) Bailer-Jones & Mundt 2001; (2) Terndrup et al. 1999; (3) Tinney & Tolley 1999; (4) Martín et al. 2001; (5) Clarke et al. 2002; (6) Gelino et al. 2002.

Gelino et al. (2002) found photometric variabilities for several L dwarfs. These features show no periodicities or at least no persistent periodicities and are therefore rather caused by rapid evolution of atmospheric features than being rotationally induced. Eislöffel & Scholz (2002) studied the photometric behavior of very low mass stars and brown dwarfs in the young ( $\sim 36$  Myr) cluster IC 4665 and report the finding of rotational periods below 1 day for five candidate brown dwarfs. Details on periods and amplitudes will be given in a forthcoming publication.

### 3. SAMPLE

The targets of our observations are 12 low-mass M6–M8-type objects, Cha H $\alpha$  1 to 12, located in the center of the Cha I star-forming cloud with an age of 1–5 Myr (Comerón, Rieke, & Neuhäuser 1999; Comerón, Neuhäuser, & Kaas 2000). Their masses are below or near the borderline separating brown dwarfs and very low mass stars. Four of them are bona fide brown dwarfs (Neuhäuser & Comerón 1998, 1999; Comerón et al. 2000). We like to note that all three brown dwarf candidates for which we are presenting rotational periods in this paper, Cha H $\alpha$  2, 3, and 6, have masses below the hydrogen burning mass limit, but they are *candidates* because the error bars of their effective temperatures extend into the stellar regime (see Comerón et al. 2000).

A first study of their rotational properties has been carried out by Joergens & Guenther (2001), who measured the rotational broadening of spectral features in high-resolution spectra obtained with the UV-Visual Echelle Spectrograph at the VLT. They found  $v \sin i$  values within the range of 8–26 km s $^{-1}$  for nine out of the 12 objects.

Furthermore, the very low mass T Tauri stars B34, CHXR 73 and CHXR 78C, in the same field of view, have been studied.

### 4. PHOTOMETRY

We monitored a 13'  $\times$  13' region in the Cha I cloud photometrically in six consecutive half-nights with DFOSC at the Danish 1.5 m telescope at ESO, La Silla, Chile. Images were obtained in the Bessel R and the Gunn  $i$  filter between 2000 May 31 and June 5. The first two nights were partly cloudy, and therefore fewer images (with lower signal-to-noise ratio [S/N]) were taken on these two nights.

The exposure times have been chosen to detect periods on timescales of expected rotational periods of the objects. Projected rotational velocities  $v \sin i$  (Joergens & Guenther 2001) indicate that their rotational periods are within the range of a few days. The objects span a large dynamical range ( $I = 13.6$ – $17.4$  mag); therefore, we obtained Gunn  $i$ -band images with two different exposure times of about 400 and about 900 s.  $R$ -band images have been taken with only one exposure time of about 1000 s.

We performed aperture photometry for the 12 bona fide and candidate brown dwarfs Cha H $\alpha$  1 to 12, the very low mass T Tauri stars CHXR 73, CHXR 78C, B34, as well as several reference stars in the field with IRAF.<sup>6</sup> The sky

background was determined from a source-free annulus and subtracted from the object counts. The T Tauri stars CHXR 74 and Sz 23 are also in the field of view but have been saturated. The calculation of differential magnitudes allowed us to compensate for variable atmospheric conditions at least to a certain degree.

Three reference stars have been chosen carefully for each filter based on the criteria of constant brightness over the time of observations, good S/N, as well as similar brightness as the targets. From the analysis of these reference stars we estimate the photometric error to be about 0.015 mag or less: the standard deviation of the reference stars is 0.009–0.014 mag in the Gunn  $i$  band and 0.005–0.006 mag in the  $R$  band (see Fig. 1 and Figs. 3–6 for the dispersion of the reference stars).

### 5. TIME SERIES ANALYSIS

We applied the string-length method (Dworetzky 1983) in order to search for periodicity in the obtained light curves of the targets. This method is ideally suited for unevenly spaced data as in our case. The algorithm phase folds the data with a trial period and calculates the string length between successive data points. This is done for all periods within a given period range. The period that generates the minimum string length is the most likely period.

The significance of the detected periods was estimated by cross-checking a randomized data set sampled with the same time steps as the real data but with arbitrary magnitudes within the limits of the real magnitudes. For each suspected period, we checked 10,000 randomized data sets. The percentage of samples that have a longer (i.e., less significant) string length for any period than that of the suspected period yields the confidence level (a 99.99% confidence level corresponds to the case that all randomized samples have a longer string length than the string length for the suspected period). Besides this significance test, a major emphasis was put on a direct check by eye of the original as well as the phase-folded light curves.

It is well known that in addition to intrinsic periodicities of the monitored objects, the light curves may show alias periods due to the sampling rate of the data. The most common alias periods  $P_{\text{false}}^{-1}$  are

$$P_{\text{false}}^{-1} = 1.0027 \text{ day}^{-1} \pm P_{\text{true}}^{-1} \quad (1)$$

(Dworetzky 1983). This equation relates the true period with possible alias periods, which are inherent to the data owing to an observing frequency of 1 sidereal day.

In general, more images have been obtained in the Gunn  $i$  band than in the  $R$  band; in addition, the Gunn  $i$ -band data have a higher S/N. Therefore for each object, first the Gunn  $i$ -band data were studied and were given a higher weight. We have searched for periods in the range of 1.5 hr to 5 days. The minimum period is set by twice the average sampling rate of about 45 minutes. The maximum is chosen to be slightly smaller than the total time coverage of about 5.5 days.

### 6. RESULTS

We have measured significant periods for three brown dwarf candidates (Cha H $\alpha$  2, 3, 6), as well as for two very low mass T Tauri stars (B34, CHXR 78C) within the range

<sup>6</sup> IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy (AURA), Inc., under cooperative agreement with the National Science Foundation.

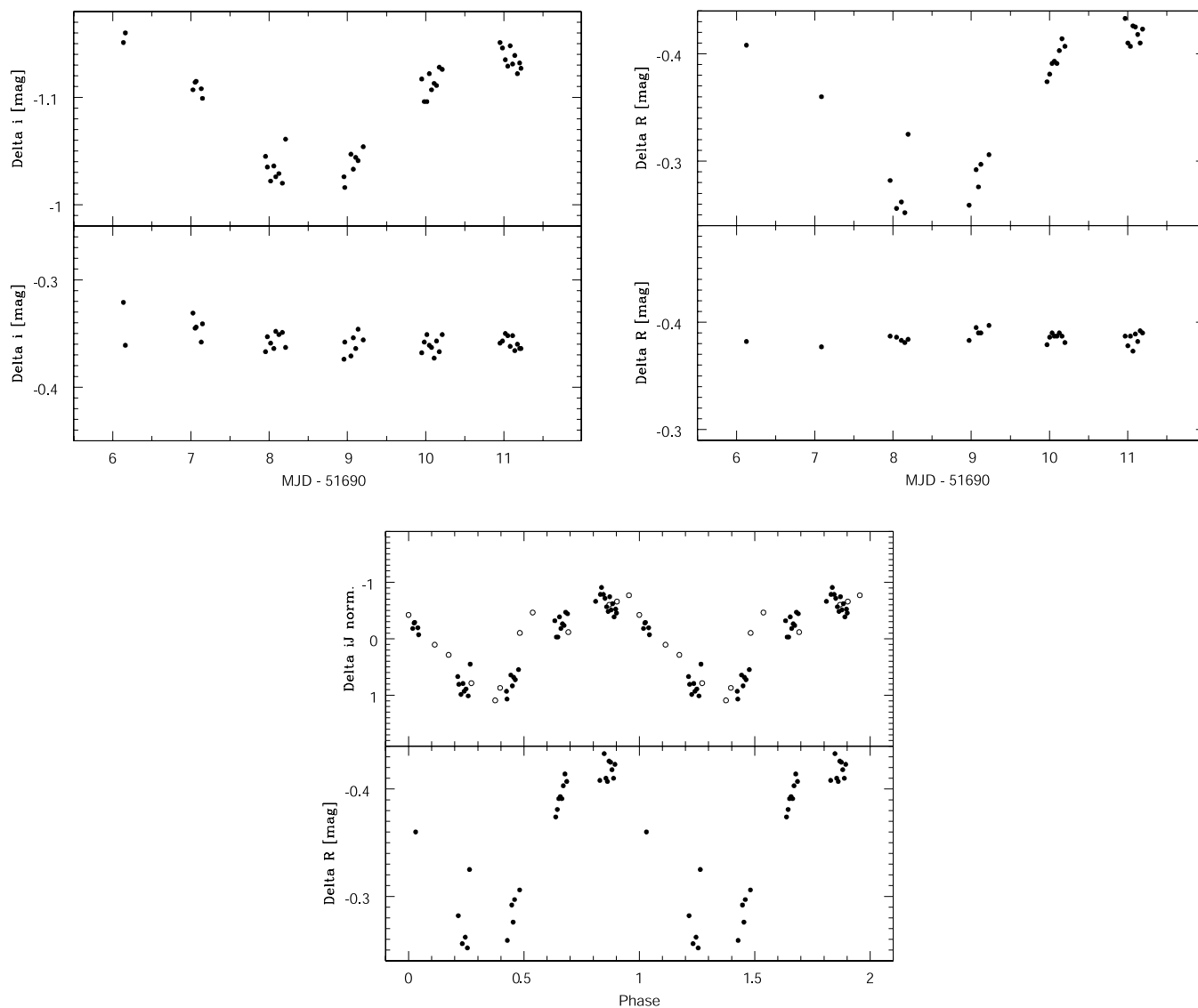


FIG. 1.—Light curves of the very low mass T Tauri star B34. *Top panels:* Gunn *i*- and *R*-band original light curves (relative magnitudes), each with reference star magnitudes plotted below for comparison. *Bottom panel:* Joined *iJ* and *R* light curves phase-folded with the determined period. *Filled circles:* Our Gunn *i* and *R* data. *Open circles:* *J*-band data from Carpenter et al. (2002).

of 2.2–4.8 days and with Gunn *i*-band amplitudes between 0.06 and 0.14 mag (Table 2 and Figs. 1, 3–6).

For Cha H $\alpha$  4, 5, 8, 12 and CHXR 73 no clear variations are detected, and limits for variability amplitudes for these objects are derived (Table 2). The S/N of Cha H $\alpha$  1, 7, 9, 10, and 11 in the obtained images is too low for a further exploitation. These objects should be reobserved with a larger telescope.

Details of the results of the period analysis on individual objects as well as original and phase-folded light curves are presented in the following subsections. Objects are ordered by decreasing mass: from about 0.12  $M_{\odot}$  for B34 to about 0.05  $M_{\odot}$  for Cha H $\alpha$  6. These masses are rough estimates based on a comparison with theoretical evolutionary tracks by Baraffe et al. (1998) for the Cha H $\alpha$  objects (Comerón et al. 2000) and by Burrows et al. (1997) for the T Tauri stars B34 and CHXR 78C (Comerón et al. 1999), respectively.

Recently, a near-infrared (*JHK<sub>S</sub>*) photometric monitoring campaign of the Cha I cloud has been carried out (Carpenter et al. 2002), which includes all the targets of our

sample. These observations contain between 11 and 25 points per target obtained in 10–12 separate nights, mostly in 2000 April and May, and for some targets (B34, CHXR 78C, and Cha H $\alpha$  3) there is an additional point in 2000 January.

After checking that the period analysis performed for our data clearly excludes periods shorter than 1 day, we have decided to take the data of Carpenter et al. (2002) into account for our analysis. Our Gunn *i*- and *R*-band light curves are well sampled but have a total time basis of less than 6 days and are therefore hardly providing strong support for periods longer than 3 days. On the other hand, the *JHK<sub>S</sub>* data include just one or two points per night but cover several weeks. Therefore, they are the ideal complement to our data set and increase the total time basis to 55–59 days (not taking into account the single measurement from 2000 January).

Since the two data sets correspond to different filters, we have joined only data taken with the Gunn *i* and *J* filters, for which the difference in effective wavelength is smaller. In

TABLE 2  
ROTATIONAL PERIODS AND PHOTOMETRIC AMPLITUDES FOR BROWN DWARFS AND VERY LOW MASS STARS IN CHA I

OBJECT	CHARACTERISTICS OF THE TARGETS				PERIODS				PHOT. AMPLITUDE		
	SpT	$M_*$ ( $M_\odot$ )	$I$ (mag)	$R_*$ ( $R_\odot$ )	$P_{\text{phot}}$ (days)	$\Delta P_{\text{phot}}$ (days)	$P_{v \sin i}$ (days)	$\Delta P_{v \sin i}$ (days)	$\Delta R$ (mag)	$\Delta i$ (mag)	$\Delta J$ (mag)
B34 .....	M5	0.12	14.3	0.93	4.75	0.38	3.1	+1.7 -1.0	0.18	0.14	0.13
CHXR 78C .....	M5.5	0.09	14.8	0.94	4.25	0.31	...	...	0.10	0.07	0.06
Cha H $\alpha$ 2 .....	M6.5	0.07	15.1	0.73	3.21	0.17	2.9	+1.4 -1.0	0.06	0.05	0.05
Cha H $\alpha$ 3 .....	M7	0.06	14.9	0.77	2.19	0.09	1.9	+0.8 -0.6	0.09	0.08	0.08
Cha H $\alpha$ 6 .....	M7	0.05	15.1	0.68	3.36	0.19	2.6	+2.0 -1.0	0.06	0.06	0.10
CHXR 73 .....	M4.5	0.15	15.6	1.46	...	...	...	...	<0.03	<0.05	...
Cha H $\alpha$ 4 .....	M6	0.1	14.3	0.89	...	...	...	...	<0.03	<0.03	...
Cha H $\alpha$ 5 .....	M6	0.1	14.7	0.83	...	...	...	...	<0.04	<0.02	...
Cha H $\alpha$ 8 .....	M6.5	0.07	15.5	0.59	...	...	...	...	<0.02	<0.04	...
Cha H $\alpha$ 12 .....	M7	0.05	15.6	0.66	...	...	...	...	<0.04	<0.03	...

NOTES.—Spectral types (SpT), masses ( $M_*$ ), and  $I$ -band magnitudes are from Comerón et al. 1999, 2000. Masses are estimates on the basis of Baraffe et al. 1998 tracks for the Cha H $\alpha$  objects and on Burrows et al. 1997 tracks for the T Tauri stars, respectively. Radii ( $R_*$ ) are estimated on the basis of luminosities and effective temperatures from Comerón et al. 1999, 2000; their errors are on the order of 30%. Rotational periods ( $P_{\text{phot}}$ ) and photometric peak-to-peak amplitudes ( $\Delta R$ ,  $\Delta i$ ,  $\Delta J$ ) are derived from our Gunn  $i$ - and  $R$ -band light curves taking into account  $J$ -band data from Carpenter et al. 2002.  $\Delta P_{\text{phot}}$  is an upper limit for the error of the derived periods based on Nyquist's frequency.  $P_{v \sin i}$  denotes rotational periods derived from radii and  $v \sin i$  measurements (Joergens & Guenther 2001);  $\Delta P_{v \sin i}$  is a  $1 \sigma$  error. Note that  $\Delta i$  refers to our Gunn  $i$  photometry, whereas the  $I$ -band magnitudes by Comerón et al. are obtained in the Cousins  $I$  filter. For CHXR 78C no  $v \sin i$  measurements are available. See the text for more details.

order to deal with the differences in amplitude and average brightness of the objects in the two different bands, we have normalized each data set by subtracting its mean and dividing by its standard deviation.<sup>7</sup>

Thereafter, we have carried out a period analysis of the objects in the so-created joined Gunn  $i$  and  $J$  data set. The results are given for each object at the end of the corresponding subsection. Upper limits for the error of the period determinations have been computed from Nyquist's frequency based on a time basis of 55–59 days. They range from 9 to 2 hr. The error bars of the  $J$ -band data, except for B34, are between a factor 0.3 and 0.4 of the amplitude observed in that band. For B34 the error bars are smaller, namely, between a factor 0.15 and 0.23 of its  $J$  amplitude.

Only for the plots, the normalized  $iJ$  light curves have been additionally divided by their amplitudes for clarity.

### 6.1. B34 ( $\sim 0.12 M_\odot$ )

The brightness of the T Tauri star B34 varies with a peak-to-peak amplitude of 0.14 mag in the Gunn  $i$  band and 0.18 mag in the  $R$  band during the six nights of our observations (Fig. 1). The light curves show a smooth variability apart from one runaway data point in the third night, which is present in both filters and shows a larger deviation in the  $R$  band than in the Gunn  $i$  band, which is consistent with an intrinsic increase of the brightness due to a flarelike event.

The period search analysis of the Gunn  $i$  light curve of B34 yields a clear period of 4.5 days with a confidence level above 99.99%. Searching for periods in the  $R$ -band data yields rather a plateau with a range of 4.2–4.9 days for the string length than a clear minimum; i.e., the period search algorithm is unable to distinguish between the significance of periods within this range. This can be understood if one takes into account that these periods are very close to the

total time basis of the data set ( $\sim 5.5$  days) and that the  $R$ -band brightness of the first two nights is only constrained by one data point each. Therefore, any errors of these points greatly affect the period search.

The period analysis carried out on the Gunn  $i$ - and  $J$ -joined data set solves the uncertainty of the mentioned plateau and gives  $4.75 \pm 0.38$  days as the best period. The data folded with that period are shown in Figure 1 (*bottom*). The phase-folded  $R-i$  color curve (Fig. 2) shows that B34 is redder during minimum light as expected for brightness variations caused by star spots.

### 6.2. CHXR 78C ( $\sim 0.09 M_\odot$ )

The T Tauri star CHXR 78C changes its brightness with an amplitude of 0.07 mag in Gunn  $i$  and 0.10 mag in  $R$  (Fig. 3). The period search algorithm returns a period of 4.0 days for the Gunn  $i$ -band light curve and a period of 3.9 days for the  $R$ -band light curve, both with a confidence level above 99.99%.

The period analysis carried out on the Gunn  $i$ - and  $J$ -joined data set yields a slightly longer period of  $4.25 \pm 0.31$  days. The folded Gunn  $i$ - and  $R$ -band data confirm it as the best period (Fig. 3, *bottom*).

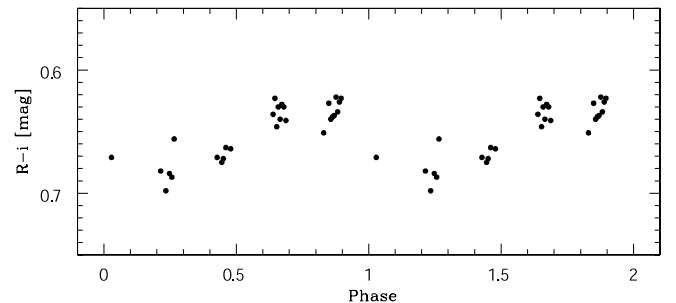


FIG. 2.—Phase-folded  $R-i$  colors of B34

<sup>7</sup> If normalization is done by subtracting the middle value of the light curve and dividing by its amplitude, the same results are obtained, but mathematically, the first method is more consistent.

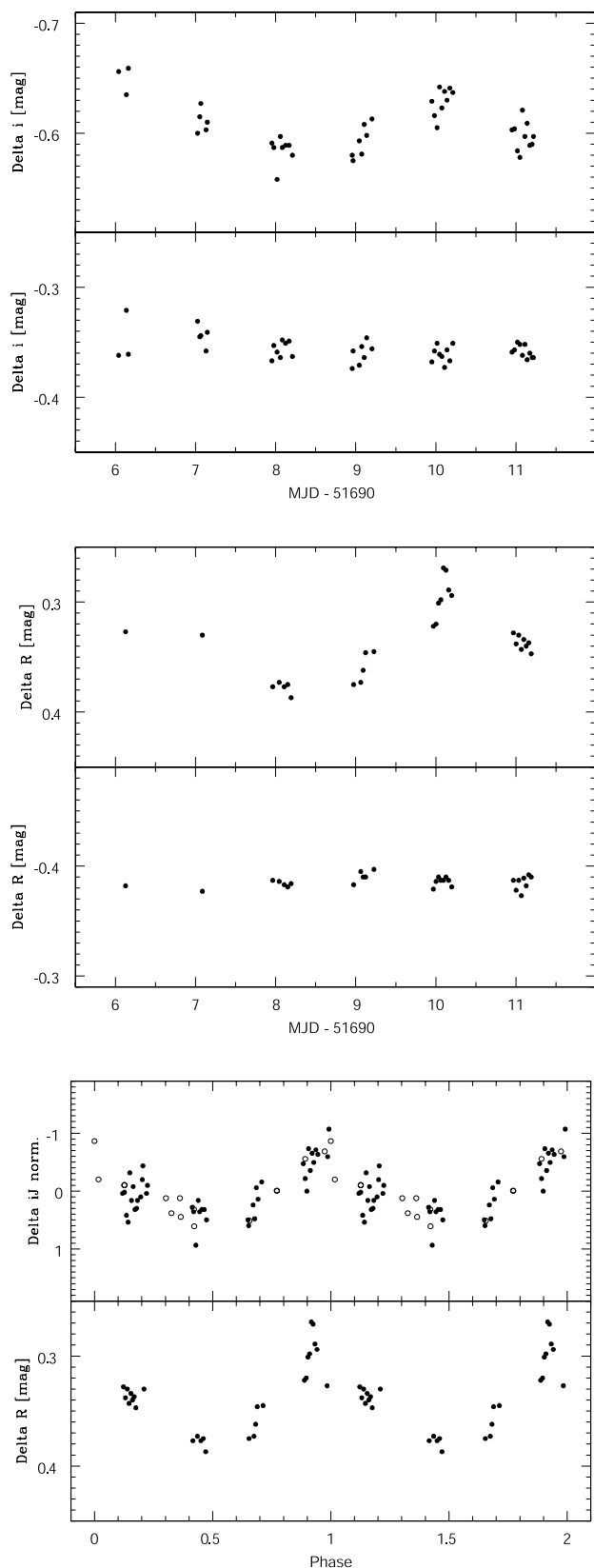


Fig. 3.—Same as Fig. 1, but for light curves of the very low mass T Tauri star CHXR 78C.

### 6.3. *Cha H $\alpha$ 2* ( $\sim 0.07 M_{\odot}$ )

In order to increase the S/N for the faint brown dwarf candidate *Cha H $\alpha$  2* we binned adjacent data points in groups of about five. Figure 4 (*top panels*) displays the original data as well as the overplotted binned data. The binned light curves have variability amplitudes of 0.05 mag in Gunn *i* and 0.06 mag in *R*. We have found a minimum string length for a period of 2.8 days for the Gunn *i*-band data with a confidence level larger than 99%. The light curves folded with this period support this result. The data analysis yields also the two less significant periods 0.73 and 1.56 days, which cannot be rejected at once by a look to the phased light curves. However, they are related with the more significant 2.8 day period by equation (1) and are therefore supposed to be alias periods inherent to the data owing to the sampling frequency of 1 day.

The *R*-band light curve of *Cha H $\alpha$  2* shows similar variations and trends as the Gunn *i*-band light curve (Fig. 4, *top right*). However, the period analysis of the *R*-band data does not confirm the 2.8 day period on a high confidence level. It gives a minimum string length for 1.6 days (the alias in the Gunn *i* band) and only a second minimum for 2.8 days. The enhancement of the alias compared to the true period can be attributed to the smaller number of *R*-band images as well as their lower S/N.

The period analysis for this target carried out on the Gunn *i*- and *J*-joined data set gives  $3.21 \pm 0.17$  days as the best period. The Gunn *i*- and *R*-band data folded with this period show a smooth curve (Fig. 4, *bottom*).

We note that there are hints in *Hubble Space Telescope* images of *Cha H $\alpha$  2* that it may be a close 0".2 binary (Neuhäuser et al. 2002) unresolved in our DFOSC aperture photometry. If this is confirmed, the period found for *Cha H $\alpha$  2* is presumably the period of one of the two components or a combination of both.

### 6.4. *Cha H $\alpha$ 3* ( $\sim 0.06 M_{\odot}$ )

The brown dwarf candidate *Cha H $\alpha$  3* exhibits variations with a Gunn *i* amplitude of about 0.08 mag and an *R* amplitude of about 0.09 mag (Fig. 5). The Gunn *i*-band flux of this object seems to be modulated with a clear sine wave. However, the first three data points in the second night deviate from this behavior. The period analysis without these three points yields a highly significant period of 2.2 days with a confidence level above 99.99%. This suggests that 2.2 days is an intrinsic period to this object, although strong reasons have not been found to reject the three deviant data points.

The *R*-band data reflect the general trends also seen in the Gunn *i* band but are more noisy. They support a period of 2.2 days but do not confirm it with high significance. The *R*-band data of nights 3–6 show a minimum string length for a period of 0.06 days, but this can be rejected on the basis of a check of the data folded with this period. There is a second minimum at 2.2 days, and the *R*-band data folded with 2.2 days look quite smooth.

The period analysis carried out on the Gunn *i*- and *J*-joined data set yields a period of  $2.19 \pm 0.09$  days for *Cha H $\alpha$  3*, after discarding one single outlying *J* data point. The light curves of this object folded with the derived period also confirm the result and are displayed in Figure 5 (*bottom*). The outlying *J* data point was included again for

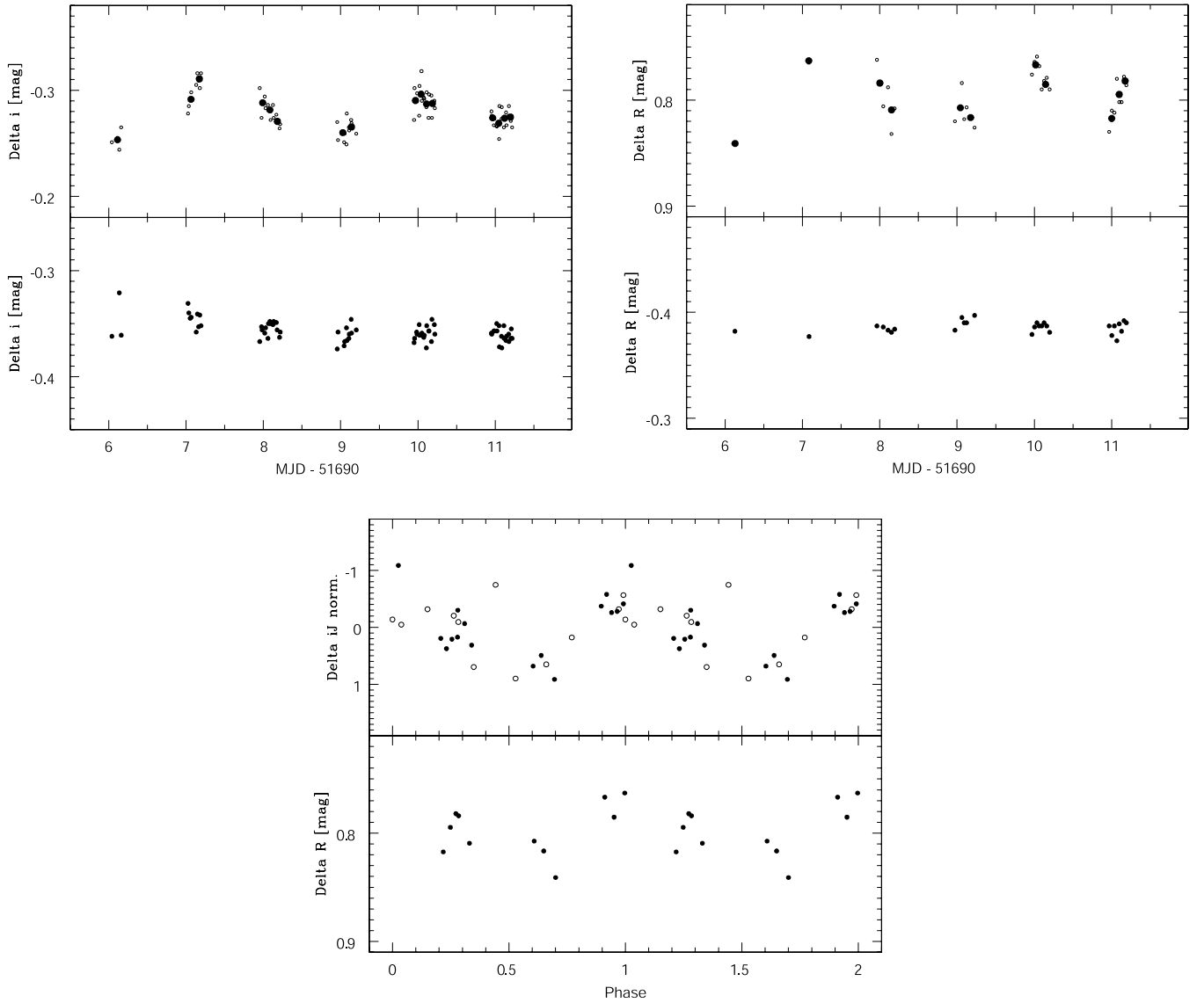


FIG. 4.—Light curves of the brown dwarf candidate Cha H $\alpha$  2. Panels are as in Fig. 1. Filled circles in the Gunn  $i$  and  $R$  light curves (*top panels*) represent an average of the original data points (*open circles*).

the plot for completeness. It is the lowest one in the joined  $iJ$  light curve at a phase of about 0.55.

### 6.5. Cha H $\alpha$ 6 ( $\sim 0.05 M_{\odot}$ )

In order to increase the S/N of the brown dwarf candidate Cha H $\alpha$  6, we binned adjacent data points in groups of two or three. See Figure 6 (*top panels*) for the original data and the overplotted binned data. The binned data of the object shows variabilities with an amplitude of 0.06 mag in both bands. The study of periodicities for the Gunn  $i$ -band data results in a minimum string length for a period of 3.49 days with a confidence level of 96%. There are two less significant minima at 0.77 and 1.43 days, which are related to the 3.49 day period by equation (1). The analysis of the  $R$ -band data is hampered by the small number of data points. Particularly on the first night there is only a single data point that has a large uncertainty owing to the poor weather conditions. We ignored it for the further analysis of the  $R$ -band data and the search for periods. We find a minimum string length for a period of 3.34 days and two less

significant minima for 0.78 and 1.58 days. The alias periods for 3.34 days are 0.77 and 1.42 days; therefore, 0.78 and 1.58 may be aliases.

The period analysis carried out for the Gunn  $i$ - and  $J$ -joined data set reproduces exactly the period that was obtained for the Gunn  $i$ - and  $R$ -band data,  $3.36 \pm 0.19$  days. The confidence level is 99.99%. The phase-folded light curves of Cha H $\alpha$  6 also confirms it as the best period (see Fig. 6, *bottom*).

## 7. DISCUSSION

The periods measured for Cha H $\alpha$  2, Cha H $\alpha$  3, and Cha H $\alpha$  6 are among the first photometric periods determined for very young substellar objects and the longest found for any brown dwarf so far. Furthermore, the objects have relatively large variability amplitudes compared to hitherto monitored brown dwarfs. Causes of these variations as well as constraints for the evolution of angular momentum in the substellar regime are discussed in the following sections.

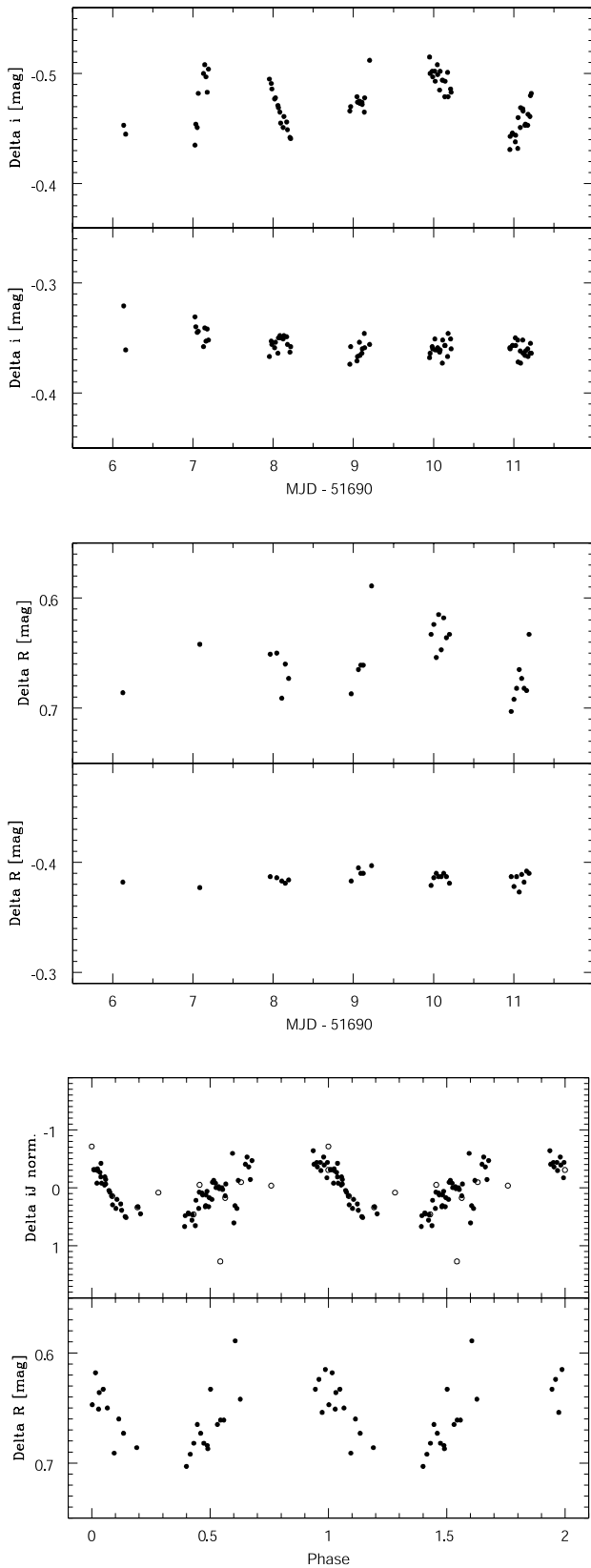


FIG. 5.—Same as Fig. 1, but for light curves of the brown dwarf candidate Cha H $\alpha$  3.

### 7.1. Rotational Modulation Due to Spots

We interpret the detected periodic photometric variations of the brown dwarf candidates as well as of the T Tauri stars as rotational modulation of the emitted flux due to surface spots based on the following arguments:

1. The detected periods are consistent with rotational velocities  $v \sin i$  and are therefore likely rotational periods. See § 7.2 for more details.

2. The monitored  $R-i$  colors of these objects show larger amplitudes for shorter wavelength in agreement with the expectations for spots. This is true for all but Cha H $\alpha$  6, which shows the same amplitude in both the Gunn *i* and *R* bands. Nevertheless, there may be slight differences between the amplitudes in the two bands, which are swallowed by the measurements uncertainties. The *J*-band amplitudes based on the data by Carpenter et al. (2002) for the same objects are always smaller or similar than those observed in the Gunn *i* band also in agreement with spots. Only for Cha H $\alpha$  6, the *J*-band amplitude is apparently slightly larger than the Gunn *i* amplitude. However, the fact that the *J*-band data have larger photometric errors than the *R* and Gunn *i* data could very well account for the larger *J*-band amplitude for Cha H $\alpha$  6.

3. Young, pre-main-sequence stars are known to have dominant surface features (e.g., Bouvier et al. 1993 and references therein), which are attributed to magnetic dynamo action. Although the brown dwarfs as well as the T Tauri stars studied in this paper have very low masses, they are relatively hot due to their young age. Thus, the atmospheric temperatures may be hot enough for a sufficient ionization fraction of the plasma in the atmospheres to allow for magnetically induced surface features. (It should be noted that the dynamo operating in fully convective objects, like pre-main-sequence stars, stars of lower mass than  $\sim 0.4 M_{\odot}$  and brown dwarfs, is not yet completely understood.)

4. The temperatures of these young objects are too hot (between 3030 K for B34 and 2840 K for Cha H $\alpha$  3 and 6) for significant dust condensation according to model atmosphere calculations (e.g., Tsuji et al. 1996a, 1996b; Allard et al. 1997; Burrows & Sharp 1999). Therefore, nonuniform condensate coverage that has been suggested to explain the photometric variability detected for some L and M-type old and hence cool (brown) dwarfs (Tinney & Tolley 1999; Bailer-Jones & Mundt 2001; Martín et al. 2001; Clarke et al. 2002) is an unlikely cause for the variabilities detected by us for the studied Cha I objects.

### 7.2. Comparison with Spectroscopic Velocities $v \sin i$

As mentioned above, the detected periods for Cha H $\alpha$  2, 3, 6, and B34 are consistent within the measurements uncertainties with their projected rotational velocities  $v \sin i$  of 12.8, 21.0, 13.0, and 15.2 km s $^{-1}$ , respectively (Joergens & Guenther 2001). This indicates that they are likely rotational periods of the objects (for CHXR 78C no  $v \sin i$  measurement is available). Rotational periods  $P_{v \sin i}$ , which are upper limits of the true rotational periods have been derived from radii and  $v \sin i$  values and are given in Table 2. The radii have been determined based on luminosities and effective temperatures from Comerón et al. (1999, 2000) applying the Stefan-Boltzmann law.

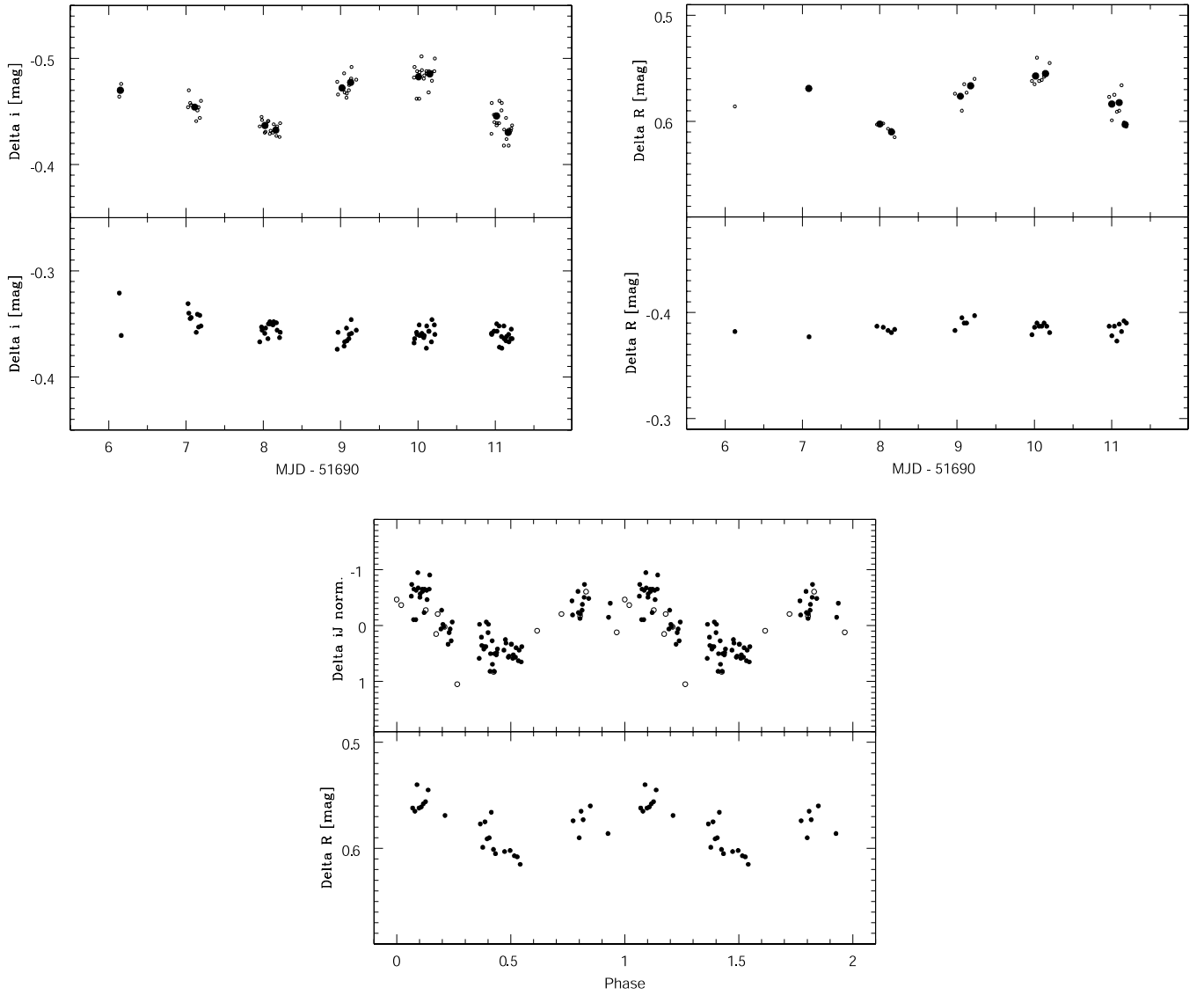


FIG. 6.—Light curves of the brown dwarf candidate Cha H $\alpha$  6. Panels are as in Fig. 1. Filled circles in the Gunn  $i$  and  $R$  light curves (*top panels*) represent an average of the original data points (*open circles*).

It is noteworthy that the observed periods  $P_{\text{phot}}$  are always—with the exception of Cha H $\alpha$  2—larger than the calculated periods  $P_{v \sin i}$  but do still agree with them when the errors are taken into account, hinting at a systematic effect. A  $1 \sigma$  error of  $P_{v \sin i}$  with propagated errors of the luminosity, the effective temperature ( $\Delta \log L_{\text{bol}}/L_{\odot} = 0.175$ ,  $\Delta T = 150$  K; Comerón et al. 2000) and  $v \sin i$  ( $\Delta v \sin i = 1\text{--}3$  km s $^{-1}$ ; Joergens & Guenther 2001) is given in Table 2. Since  $P_{v \sin i}$  scales with  $(L_{\text{bol}})^{1/2}$ ,  $T_{\text{eff}}^{-2}$ , and  $v \sin i^{-1}$ , reasons for systematic deviations of the estimated  $P_{v \sin i}$  from the observed  $P_{\text{phot}}$  may be either that the luminosities (bolometric correction, distance) have been systematically underestimated, the rotational velocities  $v \sin i$  have been systematically overestimated, the effective temperatures have been systematically overestimated, and/or the radii are systematically too small.

### 7.3. Radii of Brown Dwarfs

The radii of the very young brown dwarfs and brown dwarf candidates Cha H $\alpha$  1 to 12 estimated from luminosi-

ties and effective temperatures are ranging from  $0.3 R_{\odot}$  for Cha H $\alpha$  11 ( $\sim 0.03 M_{\odot}$ ) to  $0.9 R_{\odot}$  for Cha H $\alpha$  4 ( $\sim 0.1 M_{\odot}$ ). The uncertainties are on the order of 30% owing to propagated errors in the luminosities and effective temperatures. Their relatively large radii are fully consistent with the extremely young age of the objects and the fact that they are still in a contracting stage. Models of Chabrier & Baraffe (1997) show that a brown dwarf with a mass of  $0.06 M_{\odot}$  has a radius of  $\sim 0.55 R_{\odot}$  at 3 Myr and a radius of  $\sim 0.45 R_{\odot}$  at 5 Myr in their calculations. Only after  $\sim 500$  Myr, brown dwarfs have more or less shrunk to their final size at a radius of  $\sim 0.1 R_{\odot}$  independent of their mass (Chabrier et al. 2000).

Bailer-Jones & Mundt (2001) studied the photometric variability of late-M and L dwarfs, among them several very young objects in  $\sigma$  Orionis. The authors claim that none of the objects in their sample has a radius larger than  $0.2 R_{\odot}$ . On the basis of this radius assumption and on spectroscopic velocities  $v \sin i$  of 10–60 km s $^{-1}$ , as found by Basri et al. (2000) for late-M and L dwarfs in the field, they infer expected rotational periods for their targets on the order of

1–10 hr (see also § 7.4). However, the radii for the  $\sigma$  Orionis objects in their sample, which have an age of 1–5 Myr and masses between 0.02 and 0.12  $M_{\odot}$ , are certainly larger than 0.2  $R_{\odot}$ . This is not only shown by a comparison with theoretical models (e.g., Chabrier et al. 2000), but there is also observational evidence for it from the study of the L1.5 dwarf S Ori 47. Estimations of its effective temperature and luminosity (Zapatero Osorio et al. 1999) indicate that the radius, even for this very low mass brown dwarf ( $\sim 0.015 M_{\odot}$ ), is on the order of 0.35  $R_{\odot}$ . The S Ori objects studied by Bailer-Jones & Mundt (2001) are of significantly higher mass than S Ori 47 and have therefore most certainly much larger radii than it.

#### 7.4. Evolution of Angular Momentum

In the current picture of angular momentum evolution, young solar-mass stars as well as brown dwarfs are supposed to undergo a spin-up because of contraction on the Hayashi track. Interaction with an accretion disk can hold up the acceleration of the rotation by magnetic braking until the inner disk is dissipated; then the star begins to spin up. As the star ages on the main sequence, angular momentum loss through stellar winds spins down the star again. In contrast, at the very low masses of brown dwarfs, there is supposed to be no braking because of winds, which would explain the observed (very) fast rotation of old brown dwarfs, which have  $v \sin i$  values ranging from 5 up to 60  $\text{km s}^{-1}$  (Basri & Marcy 1995; Martín et al 1997; Tinney & Reid 1998; Basri et al. 2000). Furthermore, brown dwarfs with ages between about 36 Myr and 1 Gyr seem to have rotational periods shorter than 1 day (see § 2 for references). The lower age limit at about 36 Myr is set by rotational periods determined for brown dwarf candidates in the young cluster IC 4665 (Eisloffel & Scholz 2002).

However, the periods that we have measured for three brown dwarf candidates in Cha I range between 2 and 3 days and are therefore larger than any period reported up to now for such low-mass objects. The relatively long rotational periods and moderately fast rotational velocities of the brown dwarf candidates in Cha I are explained naturally within the current picture of angular momentum evolution by the fact that they are still in an early contracting stage. They may have furthermore suffered until very recently a braking due to their interaction with an accretion disk.

The comparison of our rotation periods at 1–5 Myr with those in the literature at 36 Myr and older gives first indications that most of the acceleration of brown dwarfs takes place in the first 30 Myr or less of their lifetime. It is known that Cha H $\alpha$  2 and 6 have optically thick disks (Comerón et al. 2000); therefore, magnetic braking owing to interactions with the disk may play a role for them. This is suggested by the fact that among the three brown dwarf candidates with determined periods, the one without a detected disk, Cha H $\alpha$  3, has the shortest period. If the interaction with the disk is responsible for the braking, our results and the one from Eisloffel & Scholz (2002) indicate that brown dwarf inner disks dissipate between 1–5 and 36 Myr. These limits for the timescale of disk dissipation for brown dwarfs are not inconsistent with that for T Tauri stars, which are known to dissolve their inner disks within about the first 10 Myr (e.g., Calvet, Hartmann, & Strom 2000).

Bailer-Jones & Mundt (2001) report the detection of photometric periods for the two very young (1–5 Myr) M6.5

dwarfs S Ori 31 and S Ori 33 of less than 9 hr (see Table 1) and suggest that these might be rotational periods of the objects. However, as described in § 7.3, a radius of less than 0.2  $R_{\odot}$  is unreliable for the young S Ori objects; a value on the order of 0.5–1  $R_{\odot}$  is more consistent (e.g., Chabrier et al. 2000). If the periods of less than 9 hr for S Ori 31 and S Ori 33 are confirmed as rotational periods, their rotational velocities would be on the order of 100  $\text{km s}^{-1}$ , assuming for example a radius of 0.6  $R_{\odot}$ . This would mean that these very low mass stars rotate at a much higher speed than the brown dwarfs and brown dwarf candidates in Cha I, which have spectroscopic velocities  $v \sin i$  of 9–28  $\text{km s}^{-1}$  (Joergens & Guenther 2001) and rotational periods of 2–3 days as shown in this paper. A possible explanation for a much faster rotation of the S Ori objects compared to the brown dwarfs in Cha I despite the similar age, would be a significant difference in their disk lifetimes, at least if magnetic braking due to a circumstellar disk is an important process for them. The dissipation of circumstellar material in  $\sigma$  Orionis could be enhanced because of strong winds from the hot OB stars in this region in comparison with the Cha I region without such a hot star. Therefore, disk lifetimes could be much shorter in  $\sigma$  Orionis leading to an early spin-up and, thus, to significantly faster rotation of the S Ori objects than of the brown dwarfs and very low mass stars in Cha I.

A measurement of  $v \sin i$  of S Ori 31 and S Ori 33 would be useful to confirm their proposed very fast rotation. However, high-resolution spectroscopy for these faint objects is challenging even with large telescopes.

## 8. SUMMARY

We have determined photometric periods in the Gunn  $i$  and  $R$  bands for the three M6.5–M7 type brown dwarf candidates Cha H $\alpha$  2, Cha H $\alpha$  3, and Cha H $\alpha$  6 of 3.2, 2.2, and 3.4 days, respectively. These are the longest photometric periods found for any brown dwarf so far. If interpreted as rotationally induced, they correspond to moderately fast rotational velocities, which is fully consistent with their  $v \sin i$  values (Joergens & Guenther 2001) and their relatively large radii. Furthermore, we have detected periods for the two M5–M5.5 type very low mass stars B34 and CHXR 78C of 4.8 and 4.3 days. For the determination of the periods, in addition to our optical Gunn  $i$  and  $R$  photometry, we also took  $J$ -band data obtained by Carpenter et al. (2002) into account. Our Gunn  $i$ - and  $R$ -band data are sampled with a relatively high frequency ( $\sim 0.5$  hr) but have a relatively short time base (5.5 days), whereas the  $J$ -band data consist of 10–24 data points spread over 41 nights immediately before our observations and are therefore ideally complementing our data and increasing the total time coverage to 55–59 days.

The observed periodic variations of the brown dwarf candidates as well as of the T Tauri stars are interpreted as modulation of the flux at the rotation period due to magnetically driven surface features on the basis of a consistency with  $v \sin i$  values as well as  $R-i$  color variations typical for spots. Furthermore, the temperatures even for the brown dwarfs in the sample are relatively high ( $> 2800$  K) because the objects are very young. Therefore, the atmospheric gas should be sufficiently ionized for the formation of spots on one hand, and the temperatures are too high for significant dust condensation and hence variabilities due to clouds on

the other hand. These first indications for surface spots on very young brown dwarfs support the overall picture of magnetic activity of brown dwarfs, which is emerging in the last years: old (cool) brown dwarfs tend toward an absence of persistent activity, whereas very young brown dwarfs seem to have more in common with T Tauri stars as they are relatively active in terms of X-ray emission (e.g., Neuhäuser et al. 1999) and  $H\alpha$  emission.

Estimation of the radii for the bona fide and candidate brown dwarfs Cha H $\alpha$  1 to 12 show that they are relatively large ( $0.3\text{--}0.9 R_{\odot}$ ) for such low-mass objects. They are fully consistent with theoretical calculations of the contraction timescales of such very young brown dwarfs and objects near the hydrogen burning mass limit.

The periods measured by us provide valuable data points in an as-yet (in terms of rotational characteristic) almost unexplored region of the age-mass diagram. A comparison of the determined rotational periods at the age of a few million years with rotational properties of older brown dwarfs ( $>36$  Myr; Eislöffel & Scholz 2002) shows that most of the acceleration of brown dwarfs during the contraction phase takes place within the first 30 Myr or less and suggests

that the disk dissipation for brown dwarfs occurs between 1–5 and 36 Myr.

However, a larger sample of brown dwarfs at various ages and in particular at a few million years with known rotation rates is much needed to further constrain the substellar angular momentum evolution, as well as to allow for statistics of rotation rates in connection with activity indicators.

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