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Rotational and Candidate-Eclipsing-Binary Light Curves for Pre-Main-Sequence Stars in the Chamaeleon I Star-Forming Cloud

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Abstract: We present the results of a photometric survey for variability in ten X-ray-emitting low-mass stars in the Chamaeleon region. Eight of the stars we observed are bona fide pre-main-sequence members of the ~2 Myr-old Chamaeleon I star-forming cloud. The other two stars are young with high levels of relative X-ray emission, but with discordant proper motions they are probable non-members of the cloud. In six of the stars we monitored, periodic variations on timescales of 2.5–11.5 d were detected, that we ascribe to stellar rotation and the presence of cool starspots. Two other stars, CHXR 20 and CHXR 85, show large amplitude variations at visual and near-infrared wavelengths and are candidate eclipsing binaries. Compared to the rotational properties of low-mass stars in the ≈8 Myr-old η Chamaeleontis cluster, we find that the older η Chamaeleontis stars have several times higher surface specific angular momentum than the younger Chamaeleon I stars. The apparent increase in angular momentum between ~2 and 8 Myr might be due to changes in stellar internal structure as the stars evolve, or evidence for a different rotational history between members of the two star-forming regions.

Keywords: open clusters and associations: individual (Chamaeleon I) — stars: individual (CHXR 3, CHXR 20, CHXR 33, CHXR 37, CHXR 40, CHXR 47, CHXR 53, CHXR 59, CHXR 71, CHXR 85) — stars: pre-main sequence — stars: rotation — stars: spots — binaries: eclipsing

1 Introduction

The Chamaeleon I (Cha I) star-forming region is one of the nearest sites of active star formation to Earth. Located at a distance of ≈160 pc, Cha I contains over 150 stellar and brown dwarf members (Luhman 2004). Cha I members have a median age of ~2 Myr, but there is strong evidence from Hertzsprung–Russell (H–R) diagram placement of the cloud members for objects with ages of <1 Myr, to >10 Myr. The Cha I cloud thus appears to have experienced a prolonged history of star formation, with a significant increase in activity in the past few Myr.

Despite the proximity and richness of the star formation region, little has been done to measure rotation periods of Cha I pre-main-sequence (PMS) stars. The interest in measuring periods for stars in different star-forming regions is in correlating rotation/angular momentum results with other PMS evolutionary parameters of astrophysical interest such as accretion, and the presence, nature, and lifetime of circumstellar disks. These parameters might vary in PMS stars as functions of stellar age, mass and multiplicity, and possibly the star formation environment.

Another interest is investigating the 'disk locking' connection between disks and rotation, e.g. amongst the low-mass stars of the ≈8 Myr-old η Chamaeleontis (η Cha) star cluster, Bouwman et al. (2006) found that stars with disks were predominantly slow-rotating single stars, whereas most binary primaries were fast-rotating and diskless. This result suggested that disk lifetimes were shorter in binary primaries, and that these stars had then had time to 'spin up' in rotation period. A similar though less complete correlation is observed in Cha I stars, where the disk fraction in single stars exceeds that of double stars (Damjanov et al. 2007). However, as yet this correlation does not extend to include rotational information.

Rotational studies of Cha I stars have mostly been confined to $v \sin i$ angular velocity studies (e.g. Franchini, Magazzú & Stalio 1988), although photometric periods are available for a few solar-mass stars (Bouvier et al. 1986) and very-low-mass stars and brown dwarfs (Joergens et al. 2003). Although $v \sin i$ studies allow a quick measure of 'rotation', there are a number of reasons for wanting to measure rotation periods via photometric study. Advantages include: the measurement of the actual rotational period of the star not a radius- and inclination angle-dependent surrogate; detection of long-period, slowly rotating variables that have very little rotational line

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Table 1. Summary of the Fourier analysis of the CHXR-star light curves

Star	Spectral type	Period (d)	ΔV (mag)	G_{eq} (%)	μ_α (mas yr^{-1})	μ_δ (mas yr^{-1})	SED class
Rotational variables							
CHXR 3	K3	11.5	0.12	10	−3 (5)	−7 (5)	—
CHXR 33	M0	3.47	0.06	5	−19 (5)	+5 (5)	III
CHXR 37	K7	4.24	0.04	4	−24 (5)	+4 (5)	III
CHXR 40	M1	3.86	0.08	7	−29 (5)	+8 (5)	III
CHXR 59	M3	6.04	0.06	5	−21 (5)	−1 (5)	III
CHXR 71	M3	2.56	0.06	5	−25 (5)	+4 (5)	II–III
Candidate eclipsing binaries							
CHXR 20	K6	7.70/15.4	1.70	—	−18 (5)	+1 (5)	II
CHXR 85	M5	11.0	0.80	—	—	—	II
Other stars observed							
CHXR 47	K3	—	—	—	−25 (5)	+2 (5)	II
CHXR 53	M3	—	—	—	−86 (17)	+32 (13)	III

broadening and thus often have only upper limit $v \sin i$ values; measurement of the degree of spottedness or activity in PMS stars from the amplitude and stability of the photometric variations; and the possibility that eclipsing binary stars will be detected that might otherwise be missed in a single spectroscopic observation directed at obtaining the $v \sin i$ velocity of the star.

In this paper, we present a limited photometric survey of low-mass stars in the Cha I cloud, to compliment and to compare to rotational studies of low-mass stars in other nearby star-formation regions.

2 Observations and Results

Multi-epoch V-band observations were made to measure rotation periods in a subset of the Cha I PMS stellar population that were believed, from early X-ray and spectroscopic studies, to be weak-lined T Tauri (WTT) stars without significant circumstellar disks and ongoing mass accretion (e.g. Feigelson et al. 1993; Lawson, Feigelson & Huenemoerder 1996). For WTT stars such as these, variability is driven by the rotational modulation of the stars brightness due to the presence of cool starspots that can occupy up to a few tens of per cent of the surface of the WTT star, see e.g. Skelly et al. (2008). For classical T Tauri (CTT) stars with significant mass accretion from their circumstellar disks, optical variability is instead stochastically dominated by accretion hot spots and flaring activity that in some cases might also be modulated by the rotation period of the star.

Since we undertook our photometric survey, two of the stars we observed have been claimed to be non-members by Luhman (2004), and many have been subject to observations to detect circumstellar disks, indicators of on-going accretion, and adaptive optics (AO) searches for close companions (Damjanov et al. 2007; Luhman et al. 2008). Where appropriate we discuss and update the status of these stars.

Ten late-type stars in the Cha I region, with spectral types ranging from K3 to M5, were observed in separate fields using the 1-m telescope and 1 k × 1 k SITe CCD at the Sutherland fieldstation of the South African Astronomical Observatory (SAAO) during 1999 February 2–15 and March 2–8. The principal aim of the observations was the detection of rotation periods for these stars as part of a larger investigation of rotation/angular-momentum trends as a function of age in nearby PMS clusters and associations.

Table 1 lists the stars by their CHXR designation (Feigelson et al. 1993) with spectral types adopted from various Cha I studies, notably Huenemoerder, Lawson & Feigelson (1994) and Luhman (2004). Many of these objects have alternative catalogue names from other X-ray, Hα, and infrared surveys of young stars in the Chamaeleon region. Over the three weeks of observing time at SAAO, the weather was generally photometric and on most of the nights two, and occasionally three, observations of each field were made, yielding 20–25 epochs for each of the CHXR stars. The SITe CCD has a field of view of ≈26 arcmin^2 at the $f/16$ Cassegrain focus of the 1-m telescope. At least several other stars of comparable brightness to the CHXR stars were recorded in each field, which were later used as local differential standards.

The production of the differential light curves for each star and the subsequent analysis of the photometry using the Lomb–Scargle Fourier method follows that described in detail by Lawson et al. (2001) for their analysis of multi-epoch photometry of the late-type members of the η Cha star cluster. This study made use of data obtained with the same telescope and instrumentation as employed here for the Cha I stars. Furthermore, the Cha I observations were made during an observing run that was common to some of the published η Cha observations.

Table 1 lists the results from the Fourier analysis of the observations of CHXR stars shown to be periodic variables. Of the ten stars observed, rotation periods were

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found for six stars (discussed further in Section 2.1), two stars are candidate eclipsing binaries (discussed in Section 2.2), and periods were not recovered for the remaining two stars although one of them proved to be highly variable (see Section 2.3). Table 1 also lists proper motion vectors for the stars sourced from the UCAC2 and USNO-B1 catalogues (Zacharias et al. 2004; Monet et al. 2003), and their spectral energy distribution (SED) class derived from near-infrared *Spitzer Space Telescope* IRAC and MIPS photometry (Luhman et al. 2008; Luhman, unpublished). These additional data will be introduced in Section 2.4.

2.1 Rotational Variables

For the six rotational variables, Table 1 lists the period present in the light curve following the Fourier analysis of the differential photometry, the peak-to-peak amplitude of the periodicity as determined from the best-fitting sine wave fit to the light curve, and a rough estimate of the starspot size responsible for the photometric variations given here as the minimum fractional coverage, assuming that cool starspots are driving the variations as in appropriate in WTT stars. In Table 1 $G_{\rm eq}$ is a lower limit to the starspot coverage for the rotational variables. For discussion of the proper motions and the SED class, see Section 2.4.

In the absence of multi-colour observations we cannot constrain the starspot temperature and so we assume the spots to be dark making no contribution to the luminosity of the star. This assumption yields a minimum value for the surface spot coverage. Following the nomenclature of Allain et al. (1996), the minimum spot fraction $G_{\rm eq} = 1–10^{-\Delta V/2.5}$. Spot fractions are listed as percentage coverage in Table 1. Phased light curves for all six stars are shown in Figure 1.

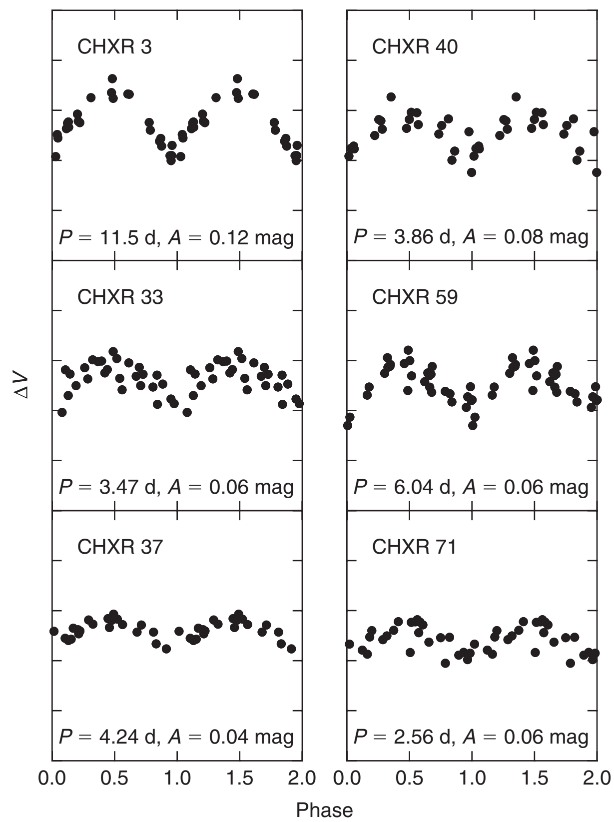

Figure 1 Phased V-band light curves for CHXR 3, 33, 37, 40, 59, and 71. Within each panel, the period and peak-to-peak amplitude determined from the Fourier analysis of the light curve is listed. Ordinate tick marks are separated by 0.1 mag. CHXR 3 is a probable non-member of the Cha I cloud. The other stars are confirmed members.

2.2 Candidate Eclipsing Binaries

Two stars in our sample, CHXR 20 and 85, have large amplitude V-band light curves that appear to be those of eclipsing binary stars; see Figure 2. In the following discussion, we assume that both stars are eclipsing systems and await the acquisition of multi-epoch radial velocities to confirm their status. If the stars are binaries, then the derived masses and radii of the components will be valuable data for comparison with the predictions of PMS evolutionary grids; see e.g. Stassun, Mathieu & Valenti (2006).

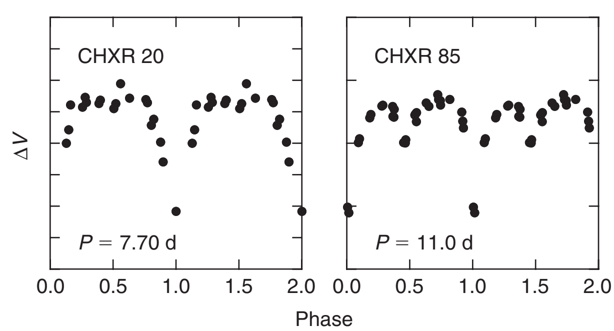

Figure 2 Phased V-band light curves for the Cha I candidate eclipsing binary stars CHXR 20 and 85. Within each panel, the period determined from the Fourier analysis of the light curve is listed. Ordinate tick marks are separated by 0.5 mag in both cases.

For CHXR 20, our photometry does not permit us to conclude if the period is 7.7 d as we show in Figure 2, with little or no evidence for a secondary eclipse, or if the period is 15.4 d with equal-depth primary and secondary eclipses. CHXR 20 is a disk source from *Spitzer Space Telescope* IRAC photometry, and is assigned an SED class of II (Damanjov et al. 2007; Luhman et al. 2008). The star was included in the 2MASS $JHK_{\rm s}$ variability study of Cha I stars by Carpenter et al. (2002). The star, catalogued as CHSM 8369 by Carpenter et al., is by a substantial margin the most variable star detected in the 2MASS study and is assigned a Stetson variability index of 12.4. The light curves show maximum amplitudes in the 2MASS bands of $\Delta J \approx 2.2$ mag, $\Delta H \approx 1.7$ mag, and $\Delta K_{\rm s} \approx 1.4$ mag, compared to our measured V-band amplitude of 1.7 mag. Although the 2MASS light curves are not well sampled, the data possibly indicate a period of $\approx$15 d. The 2MASS photometry indicates that the star is redder during eclipses. We interpret the colour variation as due to the disk making a greater contribution to the system flux during eclipse, than it would at times outside of eclipse.

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For CHXR 85, there appears to be evidence in the light curve for orbital eccentricity with the secondary eclipse occurring at a phase of ≈0.45. The primary and secondary eclipses have a similar width suggesting similarly-sized objects with a luminosity ratio of ∼3. Luhman (2004) gives a luminosity for the system of $L_{\rm bol} = 0.19\,L_\odot$. If CHXR 85AB is a few Myrs old, then the M5 spectral type CHXR 85A has a mass of 0.1–0.2 $M_\odot$ and CHXR 85B will have a mass 2–3 times lower, suggesting it might be sub-stellar in mass according to the PMS evolutionary models of Baraffe et al. (1998) and Chabrier et al. (2001). Like CHXR 20, the star has a *Spitzer*-detected disk from IRAC observations and is classified as an SED class II object (Damanjov et al. 2007; Luhman et al. 2008). The star is also variable in the near-infrared 2MASS bands, and is assigned a variability index of 3.4 by Carpenter et al. (2002) who catalogued the star as CHSM 21745. The 2MASS light curves are probably undersampling the amplitude of the variations if the data is phased at the optical period of 11.0 d (Figure 2). However, the most-concentrated series of 2MASS observations are not-inconsistent with this period. An amplitude of ≈0.4 mag is observed in J-band, with evidence for only minor variations in colour.

2.3 Stars Lacking Periods

Two other Chamaeleon stars were monitored for variability: CHXR 47 and 53.

The light curve for CHXR 47 showed significant V-band variability with a amplitude of at least 0.4 mag which led us to consider that the star might be a third candidate binary in our sample. However, no periodicity was identified in the Fourier analysis of the observations. Reasons for this could be the undersampling of any period present, or the possibility that the observed photometric variability is due to stochastic variability such as flaring, i.e. the star has properties of a CTT star. The latter explanation is consistent with the SED class II classification of the star from *Spitzer* IRAC photometry (Luhman et al. 2008).

The light curve for CHXR 53 showed little evidence for variability at levels exceeding a few hundredths of a mag, and no evidence for periodic variations. Thus CHXR 53 is the only star in our sample lacking significant photometric variations. The star is identified as a non-member of the Cha I cloud by Luhman (2004); a status we discuss further in the following sub-section.

2.4 Notes on Individual Objects

2.4.1 Probable Non-Members

A survey of the Cha I population by Luhman (2004) lists two of the ten stars we observed, CHXR 3 and 53, as non-members. CHXR 3 is listed as a background object on account of the star lacking a λ6707 Li I absorption line in medium-resolution spectroscopy; see figure 1 of Huenemoerder et al. (1994). The presence of lithium is prevalent in young PMS photospheres, and is often taken to be *the* distinguishing chemical signature delineating young PMS stars from older objects. However, every other aspect of the star suggests that CHXR 3 is young and magnetically-active. The Hα line appears partly in-filled by emission (Huenemoerder et al. 1994), the star has a $[L_X/L_{\rm bol}]$ ratio of −4.7 similar to that seen in other slow-rotating PMS stars (Wichmann et al. 1998) and, now, the measurement of an 11.5 day rotation period with a light curve amplitude that is consistent with a high spot-covering factor (this paper).

CHXR 53 is listed as a foreground object on account of the star lacking a λ6707 Li I absorption line in low signal-to-noise medium-resolution spectroscopy; see figure 1 of Huenemoerder et al. (1994). This star is unusual compared to the others monitored at SAAO in that it lacks photometric variability. This might otherwise point to the absence of magnetic activity in the star, if it were not for the presence of a high relative level of X-ray luminosity with $[L_X/L_{\rm bol}] = -3.0$ (Lawson et al. 1996). This level of relative X-ray emission, often termed the 'saturated' limit, is typical for M-type WTT stars. H–R diagram placement of CHXR 53 assigns it an age of 10 Myr if it is co-distant with the cloud (Lawson et al. 1996). The star will be older if it is closer. If the star is ≥10 Myr old then it might be one of many isolated magnetically-active stars that are seen distributed across the Chamaeleon region (e.g. Alcalá et al. 1995).

To further investigate the membership status of CHXR 3 and 53, we considered published proper motions for the stars we observed at SAAO. Table 1 lists proper motions for these stars sourced from the UCAC2 catalogue (Zacharias et al. 2004), with the exception of the proper motion for CHXR 53 which is sourced from the USNO-B1 catalogue (Monet et al. 2003). The numbers within brackets are uncertainties. For bona fide Cha members listed in Table 1, the average proper motion is $\langle \mu_\alpha, \mu_\delta \rangle = -23, +3$ mas yr^{-1}. Within the uncertainties in the proper motion vectors, the proper motions of both CHXR 3 and 53 significantly out-lie those of the Cha I stars. Together with the absence of lithium in both objects, the proper motions point to both stars being non-members consistent with their classification by Luhman (2004).

2.4.2 Accretion, Disks and Companions

The ten stars discussed in this paper were chosen as a sample of young Cha I WTT stars. For six of the stars; CHXR 20, 33, 37, 40, 59, and 85, Damjanov et al. (2007) list the Hα 10% line width and the results of an AO survey for companions. (Note that, in Damjanov et al. 2007 and Luhman 2004, CHXR 85 is named T 50.) The full width of the Hα line at 10% of the peak line is an accretion indicator, with the transition from accreting (CTT; SED class II) stars to non-accreting (WTT; SED class III) stars occurring when the Hα 10% line width falls below ∼200 km s^{-1} (Jayawardhana, Mohanty & Basri 2003). Of these six stars, only CHXR 85 has a Hα line width that is marginally in the CTT regime, at 250 ± 60 km s^{-1}, consistent with its SED class II classification (Luhman et al. 2008). The other five stars have line widths ranging from 70 to 130 km s^{-1},

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placing them nominally in the WTT regime. Of these five stars, CHXR 20 has a SED class of II, while the other four stars (CHXR 33, 37, 40, and 59) are SED class III objects indicating the absence of near-infrared excess emission (Luhman et al. 2008).

AO imaging of the six stars by Damjanov et al. (2007) found companions at projection separations of 11–24 AU for CHXR 37, 40, and 59. No details of the companions are reported, but we assume them to be significantly fainter than the primary stars and thus not affecting our photometric survey, i.e. we have measured the rotation period of the primary stars. The two eclipsing binaries, CHXR 20 and 85, do not have wider tertiary companions and are listed by Damjanov et al. (2007) as being single stars.

3 Discussion

When comparing the properties of PMS populations of different ages, the direct comparison of rotation periods is not the most appropriate measure. If stars rotationally decouple from their disks at the end of the accretion phase, then the immediate response of low-mass stars will be to 'spin up' towards faster rotation periods as they evolve through the early PMS phase due to contraction and changes in internal structure, assuming minimal angular momentum loss occurs through mechanisms such as stellar winds. Winds are thought to eventually dominate the long-term main-sequence angular momentum evolution of stars, causing them to 'spin down' again.

Instead of period, it is more appropriate to compare an angular momentum measure, and a measurement that can be derived from observations is the surface value of the specific angular momentum j, the surface angular momentum per unit mass. j is most readily expressed as equalling R^2/P, where R is the stellar radius and P the rotation period of the star. In the absence of direct measurements, the radius of a star can be determined from a measurement of luminosity L and effective temperature T_{eff} and application of the Stefan–Boltzmann law. For PMS stars, the derived value for R and therefore j varies between studies, depending on the adopted colour–temperature and colour–bolometric conversion scales, e.g. when producing Cha I H–R diagrams, Lawson et al. (1996) adopted conversions appropriate for dwarfs, whereas Luhman (2004) adopted conversions intermediate between those of dwarfs and giants.

Of the six stars with rotation periods, five are common to the Cha I population studies of Lawson et al. (1996) and Luhman (2004); CHXR 33, 37, 40, 59, and 71. The different treatments yield lower values for R and therefore j when using Lawson et al. (1996) values for L and T_{eff}, compared to those derived from values for L and T_{eff} given by Luhman (2004). However, the resulting difference in j is not great. In solar units, where $j_{\odot} = 9.5 \times 10^{11}\ \mathrm{m^2\ s^{-1}}$, the mean value of j for the five CHXR stars is 2.7 (range of 1.1–3.9; Lawson et al. 1996 values for L and T_{eff}) or $j = 4.3$ (range of 2.1–6.5; Luhman 2004 values). The only disk source amongst these five stars is the SED class II–III transitional object CHXR 71, with a j value close to the mean values.

We now compare these values for the ~2 Myr-old Cha I stars, to j values for stars in an older PMS cluster, the ≈8 Myr-old η Cha star cluster. In η Cha, rotation periods have been measured for most members (Lawson et al. 2001, 2002) and the disk fraction is well-determined from *Spitzer* IRS observations (Bouwman et al. 2006). The mean j value for all cluster members with measured rotation periods is 11.2 (range of $j = 1.9$–28.5; twelve stars). However, for η Cha stars with disks, the mean j value is 6.5 (range of $j = 2.5$–14.5; seven stars). For η Cha stars without disks, the mean value is 17.9 (range of $j = 1.9$–28.5; five stars). All high-j stars in η Cha are diskless binary primaries ($j = 21.0$–28.5; three stars).

The interesting comparison is the mean j of 2.7 (or 4.3) for the five Cha I stars, and the much higher j values for the η Cha stars. The older η Cha stars have 2–6 times the surface specific angular momentum of the younger Cha I sample, depending upon the subset of η Cha stars chosen. This difference might be a consequence of small number statistics; less than a tenth of Cha I WTT stars were measured in this survey, and several of the lowest-mass η Cha WTT stars remain unmeasured for rotation periods. But the difference, if confirmed after rotation period measurement of a larger sample of stars, might be a consequence of stellar internal structural changes in the first ~10 Myr of a PMS stars life influencing the measured surface angular momentum, or the signature of a different early rotational history between members of the two PMS associations.

4 Conclusions

We monitored ten X-ray emitting low-mass stars in Chamaeleon for photometric variability. Eight stars are bona fide members of the ~2 Myr-old Cha I star-forming cloud, while the other two are probable non-members. Amongst the ten stars we observed, six show periodic variations on timescales of 2.5–11.5 d that we ascribe to stellar rotation and the presence of cool starspots. Two of the stars are candidate eclipsing binaries, while another is variable but non-periodic. All the Cha I rotational variables we measured are slow rotators with surface specific angular momenta only a few times the solar value.

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