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CLOSE BINARIES IN THE η CHAMAELEONTIS CLUSTER[1]

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ABSTRACT

We have used speckle interferometry and adaptive optics observations to search for multiple systems among 13 stars in the η Chamaeleontis cluster. We discovered two previously unknown subarcsecond binaries. Placing the components in infrared color-magnitude diagrams shows that most members of η Cha are coeval. Repeated observations of the binary RECX 1 allow us to determine a preliminary orbit and derive a system mass of about 2 $M_{\odot}$.
Key words: binaries: general — infrared radiation — open clusters and associations: individual (η Chamaeleontis) — stars: pre–main-sequence — techniques: high angular resolution

1. INTRODUCTION

The η Chamaeleontis cluster is a recently discovered, nearby, compact group of pre–main-sequence (PMS) stars (Mamajek, Lawson, & Feigelson 1999). Four of its members have been identified as young stars in the follow-up observations of optical counterparts of X-ray sources by Alcalá et al. (1995). Mamajek et al. (1999) determined that these four stars are part of a young open cluster, together with three bright intermediate-mass stars and six additional X-ray–emitting stars found from a deep *ROSAT* High Resolution Imager observation.

Because of its proximity ($d = 97$ pc), the lack of interstellar or circumstellar extinction, and the small spread of stellar ages, the η Cha cluster provides a sensitive test for PMS evolutionary models. Lawson et al. (2001) have shown that most of the member stars form a linear sequence in the color-magnitude diagram. However, a few stars lie about 0.7 mag above this sequence and are probably unresolved binaries.

We use high angular resolution techniques, namely, speckle interferometry and adaptive optics imaging, in order to resolve multiple systems among the η Cha cluster members. The closest binaries in η Cha resolvable today are expected to have orbital periods on the order of 40 years. The determination of their orbits would give us their mass, providing another test for evolutionary models.

A preliminary report of our survey has already been given in Köhler (2001a). Here we describe our work in detail, including new observations.

2. OBSERVATIONS

The four members of η Cha from Alcalá et al. (1995) were first observed in 1996 February and March in the course of our multiplicity survey of young stars in Chamaeleon (Köhler 2001b). We used speckle interferometry in the *K* band at 2.2 μm with the SHARP I camera of the Max Planck Institute for Extraterrestrial Physics (Hofmann et al. 1992) at the ESO 3.5 m New Technology Telescope (NTT) on La Silla, Chile. This instrument provides Nyquist sampling of the diffraction limit, albeit with a field of view of only 12″ × 12″. In order to find binaries outside this field of view, we obtained additional infrared images with the IRAC2b camera at the ESO-MPIA 2.2 m telescope on La Silla in 1996 February and March, which offers a field of view of 70″ × 70″.

Seven more η Cha members were observed in the course of a multiplicity survey among *ROSAT*-detected stars located far from molecular clouds (Petr et al. 1999) with the adaptive optics system ADONIS at the ESO 3.6 m telescope on La Silla. These observations were carried out in the *K* or K_s band (central wavelengths 2.177 μm and 2.154 μm, respectively); some stars were also observed in *H* and *J* (1.643 μm and 1.253 μm). The field of view of this instrument in the configuration used is also 12″ × 12″. We obtained images of the targets at four different positions on the detector, which allows us to find companions at separations up to about 8″.

The remaining η Cha members listed by Mamajek et al. (1999), as well as ECHA J0843.3−7905 (Lawson et al. 2002), were observed on different occasions with ADONIS, when the targets of the main observing program were not high enough above the horizon to be observed. For these observations, the procedure described in the previous paragraph was used. A journal of observations is given in Table 1.

3. DATA REDUCTION

For data reduction, the binary/speckle program package[2] written by R. K. was used. The program is described in

[1] Based on observations obtained at the European Southern Observatory, La Silla, proposals 56.E-0197, 62.I-0399, 65.I-0350, 65.I-0086, 67.C-0354, and 68.C-0539.

[2] Available on the software Web page of the Center for Adaptive Optics, at http://cfao.ucolick.org/distributedsw/index.shtml, and http://babcock.ucsd.edu/cfao_ucsd/software.html.

TABLE 1
Journal of Observations

Date	Telescope	Method	Observed Objects[a]
1996 Feb 26........	ESO-MPIA 2.2 m	Imaging	RECX 7 (*J*, *H*, *K*)
1996 Feb 29........	ESO-MPIA 2.2 m	Imaging	RECX 1 (*J*, *H*, *K*), RECX 10 (*J*, *H*, *K*)
1996 Mar 4.........	ESO-MPIA 2.2 m	Imaging	RECX 12 (*J*, *H*, *K*)
1996 Mar 29.......	ESO NTT	Speckle	RECX 1 (*K*), RECX 7 (*K*), RECX 10 (*K*), RECX 12 (*K*)
1999 Jan 9..........	ESO 3.6 m	AO[b]	RECX 1 (K_s)
2000 May 29.......	ESO 3.6 m	AO	RECX 1 (*J*, *H*, K_s), RECX 7 (K_s), RECX 8 (K_s)
2000 May 30.......	ESO 3.6 m	AO	RECX 2 (K_s), RECX 4 (K_s), RECX 10 (K_s), RECX 11 (K_s)
2000 Jun 5..........	ESO 3.6 m	AO	RECX 3 (*K*), RECX 5 (*K*), RECX 6 (*K*), RECX 9 (*K*)
2001 Jun 30........	ESO NTT	Speckle	RECX 1 (*K*)
2001 Dec 9..........	ESO 3.6 m	AO	RECX 12 (*H*), ECHA J0843.3−7905 (*K*)
2001 Dec 10........	ESO 3.6 m	AO	RECX 1 (*J*, *H*, *K*), RECX 12 (*H*)
2001 Dec 11........	ESO 3.6 m	AO	RECX 7 (K_s), RECX 9 (*H*, K_s)

[a] Name of the star following the nomenclature of Mamajek et al. 1999; the filters used for the observation are given in parentheses.
[b] Adaptive optics imaging.

detail in Köhler et al. (2000). After the usual steps for reduction of infrared images (sky subtraction, correction of bad pixels, etc.), the package computes the modulus of the complex visibility (i.e., the Fourier transform of the object brightness distribution) from the power spectrum (Labeyrie 1970). The phase is computed using the Knox-Thompson algorithm (Knox & Thompson 1974) and the bispectrum method (Lohmann, Weigelt, & Wirnitzer 1983).

If an object appears unresolved (i.e., the power spectrum does not show the fringe pattern characteristic of a binary), we compute the maximum brightness ratio of a companion that could be hidden in the noise of the data. The principle is to determine how far the data deviate from the nominal result for a point source (modulus = 1, phase = 0) at several points in the (u, v)-plane. We then compute the maximum brightness ratio between the primary and a secondary that would be compatible with this amount of deviation. Separation and position angle are given by the assumption that the first minimum of the cosine-shaped fringe pattern falls onto the point where the deviation was measured. This is repeated for secondaries at the same separation, but different position angles, and the maximum is used as an upper limit for the brightness ratio of an undetected companion at a given separation. Combining the results at different separations produces the curves shown in Figure 1. (See Leinert et al. 1997 for a more detailed description of this procedure.)

If the object is a binary, we compute a multidimensional least-squares fit using the "amoeba" algorithm (Nelder & Mead 1965; Press et al. 1994) in order to determine the main binary parameters (separation, position angle, brightness ratio, and the position of the center of light). Our program tries to minimize the difference between modulus and phase computed from a model binary and the observational data by varying the parameters of the model. This is necessary because the reconstructed images are a complex function of the two-dimensional separation vector and flux ratio that cannot be solved to compute the binary parameters directly from the data. Fits to different subsets of the data yield an estimate for the standard deviation of the binary parameters. We then subtract the contribution of the companion from the images and apply the procedure described in the previous paragraph to find limits for the brightness of an undetected second companion.

4. RESULTS

4.1. *Companions and Sensitivity Limits*

Table 2 lists companions to η Cha stars and their separations, position angles, and flux ratios. We can detect companions with separations between 0.″13 (the diffraction limit of a 3.5 m telescope in the *K* band) and about 8″ (the distance between the target and the edge of the field of view of ADONIS).[3] In total, we find three companions that are to the best of our knowledge new discoveries in this work. However, it is not clear whether all companions are actually physically bound (see § 4.3).

Figure 1 shows the limits for the brightness of undetected companions as function of the separation from the primary, obtained using the algorithm described in § 3. The quality of the correction of an adaptive optics system and of the results of speckle interferometric observations depends on the brightness of the target. Since our objects cover a considerable range of magnitudes, the sensitivity of our observations is also quite different. In the worst case, we can detect companions with 10% of the flux of the primary, which corresponds to a magnitude difference of 2.5 mag.

4.2. *Photometry*

Table 3 lists near-infrared photometric data for our targets. Magnitudes of three of the sources are given by Alcalá et al. (1995). During our observations in 1996 February and March, several photometric standard stars were observed on each night except February 26. This allows us to measure zero points and extinction coefficients and to obtain calibrated photometric data of the stars in η Cha observed on

[3] The IRAC2b camera allows us to find companions at much larger separations, but only four of our stars have been observed with that instrument.

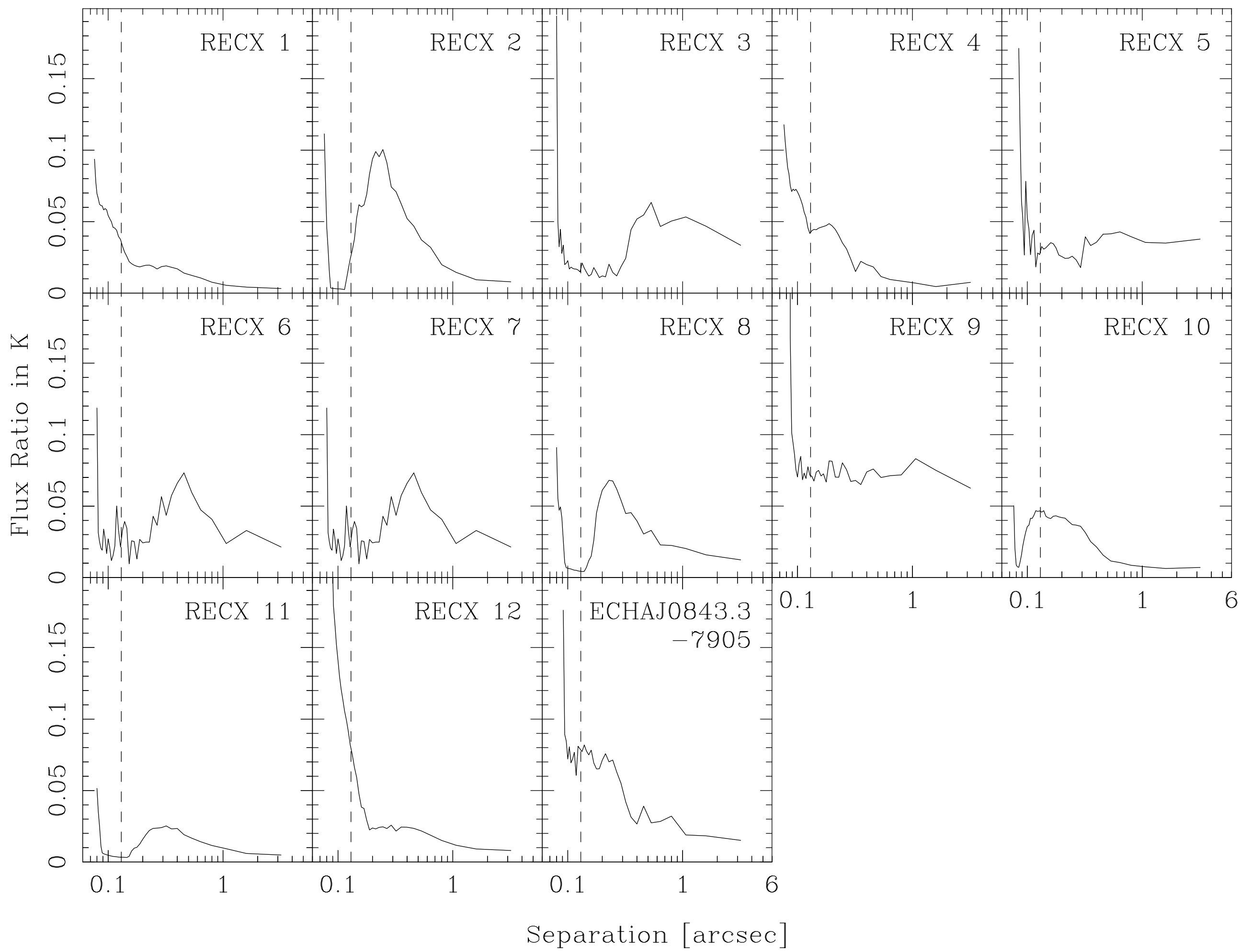

Fig. 1.—Limits on the brightness of undetected companions as a function of separation. In the case of the close binaries RECX 1 and RECX 9, the contribution of the secondary has been subtracted. For stars that were observed more than once, the best result is shown. The dashed vertical lines mark the diffraction limit of a 3.5 m telescope in the *K* band (0″13).

these nights. In 2001 December, we observed only two photometric standard stars on each night, not enough to derive reliable extinction coefficients. Therefore, we use our data to measure the zero points and take extinction coefficients from the SOFI/NTT Web site. The conditions during the other observing runs were not photometric, and therefore the data cannot be used to obtain information about the absolute photometry of the stars.

TABLE 2
Binary Stars Found in η Chamaeleontis

Name	Date of Observation	Filter	Separation (arcsec)	Position Angle[a] (deg)	Brightness Ratio
RECX 1AB..........	1996 Mar 29	K	0.135 ± 0.003	15.9 ± 1.8	0.805 ± 0.024
	1999 Jan 9	K_s	0.170 ± 0.001	187.0 ± 0.2	0.955 ± 0.011
	2000 May 29	K_s	0.180 ± 0.001	183.1 ± 0.3	0.901 ± 0.014
		H	0.179 ± 0.001	182.4 ± 0.4	0.902 ± 0.021
		J	0.179 ± 0.001	183.9 ± 0.7	0.840 ± 0.039
	2001 Jun 30	K	0.187 ± 0.001	0.5 ± 0.3	0.843 ± 0.024
	2001 Dec 10	K	0.185 ± 0.001	0.2 ± 0.2	0.948 ± 0.006
		H	0.184 ± 0.001	0.3 ± 0.3	0.923 ± 0.011
		J	0.183 ± 0.001	0.1 ± 0.5	0.772 ± 0.033
RECX 1AB-C......	1996 Feb 29	K	8.607 ± 0.009	12.9 ± 0.1	0.030 ± 0.001
	2000 May 29	K_s	8.629 ± 0.035	13.2 ± 0.2	0.021 ± 0.001
RECX 9	2000 Jun 5	K	0.210 ± 0.006	14.1 ± 1.4	0.48 ± 0.16
	2001 Dec 11	K_s	0.244 ± 0.008	14.0 ± 1.0	0.50 ± 0.10

[a] Modulo 180° (see § 4.4.1).

TABLE 3
Near-Infrared Photometry

Name	m_J	m_H	m_{K_s}	m_K	Reference[a]
RECX 1A + 1B..............	8.14 ± 0.06	7.51 ± 0.04	...	7.33 ± 0.03	Alcalá et al. 1995
	8.31 ± 0.02	7.76 ± 0.02	...	7.50 ± 0.02	1996 Feb 29
	8.17 ± 0.03	7.53 ± 0.04	...	7.39 ± 0.04	2001 Dec 10
RECX 1C	11.27 ± 0.05	10.68 ± 0.24	...	10.56 ± 0.05	1996 Feb 29
RECX 7	...	...	7.72 ± 0.05	...	2001 Dec 11
RECX 9	...	9.81 ± 0.05	9.50 ± 0.05	...	2001 Dec 11
RECX 10	9.61 ± 0.06	8.93 ± 0.04	...	8.72 ± 0.04	Alcalá et al. 1995
	9.80 ± 0.03	9.26 ± 0.04	...	8.93 ± 0.02	1996 Feb 29
RECX 12	9.30 ± 0.06	8.62 ± 0.04	...	8.38 ± 0.03	Alcalá et al. 1995
	9.34 ± 0.02	8.84 ± 0.10	...	8.40 ± 0.04	1996 Mar 4
	...	8.72 ± 0.04	...	...	2001 Dec 9
	...	8.67 ± 0.04	...	...	2001 Dec 10
ECHA J0843.3−7905.......	...	...	...	9.19 ± 0.04	2001 Dec 9

[a] If a date is given, the data were obtained from our own observations.

4.3. *Chance Alignment with Background Stars*

Since we do not measure orbital motion for most of the binaries, we cannot say whether the companions are actually bound to the primary, or if they are background stars that just happen to be located near one of our targets. To estimate the number of chance alignments, we make use of the surface density of background stars. The preliminary database of the Deep Near Infrared Survey (DENIS; Epchtein et al. 1999) contains two fields in the area of the η Cha cluster. We counted the number of stars in an area of 250 arcmin^2 near the cluster and obtained a density of 1.65×10^{-4} arcsec^{-2}. The limiting magnitude of DENIS is 14.0 mag in K_s and 16.5 mag in J, much fainter than all the companions described here.

If we assume that the number of background stars in a given area follows a Poisson distribution, then the probability of finding one background star within 9″ separation from one of our 13 targets is approximately 32%. This does not allow us to conclude without doubt that RECX 1C is a bound companion or a background star. However, its location in the J versus $J-K$ diagram (see § 5.1) indicates that it is probably not a member of the η Cha cluster.

The probability of finding a background star within 0″.2 is only 2.7×10^{-4}, that is, we can safely assume that both close binaries are indeed physically bound.

4.4. *Notes on Individual Objects*

4.4.1. *RECX 9*

RECX 9 is one of the faintest stars in our survey, and as such the signal-to-noise ratio of the data is much smaller than for the brighter binaries. Because of this, it is impossible to reconstruct a reliable phase of the Fourier-transformed image. Without the phase information, there is a 180° ambiguity in the position angle. In the case of RECX 9, we cannot tell whether the position angle is 14° or 194°. The determination of separation and flux ratio does not have a similar problem, although the precision of the results suffers from poor signal-to-noise ratio.

4.4.2. *RECX 12*

RECX 12 is suspected to be a binary, since it is located about 0.7 mag above the sequence of most η Cha members in the Hertzsprung-Russell diagram (Lawson et al. 2001). Our 1996 data show some indications that it is indeed a binary with a separation somewhat smaller than the diffraction limit. We cannot claim that we actually resolved the system, and we are unable to give a precise separation and flux ratio. We observed RECX 12 again in 2001 December, this time in the H band to take advantage of the higher resolution at shorter wavelengths. Unfortunately, the results show no sign of binarity at all. This result can be explained in two ways: either the tentative detection in 1996 was spurious, or orbital motion brought both components so close together that we cannot resolve them. To finally settle this question, observations with higher angular resolution are necessary.

5. DISCUSSION

5.1. *Color-Magnitude Diagrams*

We use the photometric data listed in Table 3 to place the stars in infrared color-magnitude diagrams (CMDs), shown in Figures 2 and 3. For comparison, evolutionary tracks

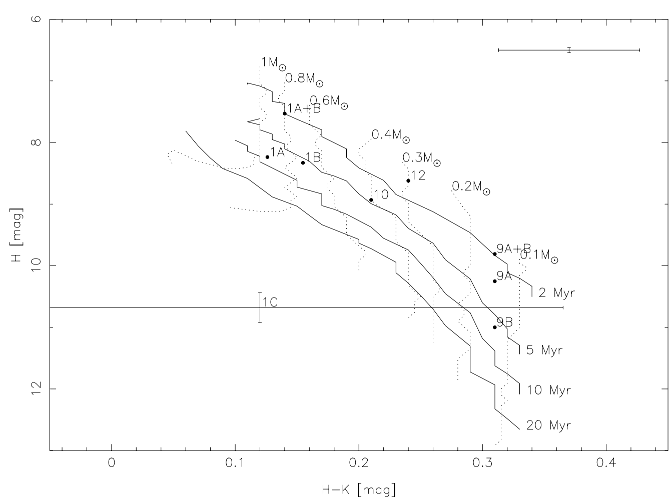

Fig. 2.—Magnitudes in the H band vs. $H-K$ colors. Typical errors for the brighter stars are shown by the error bars in the upper right corner. We assumed that the flux ratio of RECX 9 in H is the same as in K_s and used the K_s magnitudes instead of K. Therefore, for RECX 9A/9B, the errors are 4–5 times larger than for the brighter stars.

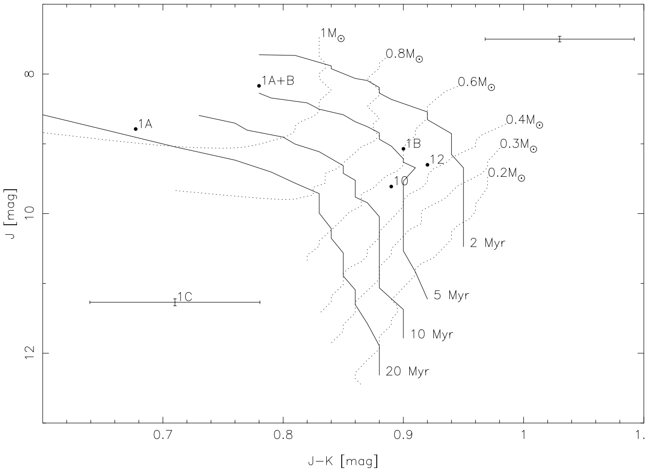

FIG. 3.—Magnitudes in the J band vs. $J-K$ colors. Typical errors for all stars except RECX 1C are shown by the error bars in the upper right corner.

and isochrones from Baraffe et al. (1998) are plotted. We selected the tracks from these authors because they give magnitudes in the J, H, and K bands, which avoids the additional uncertainty of applying a bolometric correction.

The H versus $H-K$ diagram demonstrates why it is important to resolve binary systems into their components before placing them in a CMD: the combined light of RECX 1A + 1B and RECX 9A + 9B indicates an age of 2 Myr, while the individual components lie near the 5 Myr isochrone (note that the colors of 9A and 9B are uncertain, since we were unable to measure the flux ratio in H). This shift in age makes them coeval with other members of the η Cha cluster. The exception is RECX 12, which is why we suspect it to be an unresolved binary (see § 4.4.2).

The most important aspect of the J versus $J-K$ diagram is the location of RECX 1C far from the other η Cha members. We take this as indication that RECX 1C is a background star unrelated to RECX 1AB.

5.2. *The Orbit of RECX 1*

We observed RECX 1A and 1B on five different occasions between 1996 March and 2001 December (see Table 2). The observations in the years 1999 and 2000 are somewhat peculiar, since the position angle is off by about 180° compared with the other measurements. However, the flux ratios show that the two components have nearly equal brightness, and one or both of them are variable. If we assume that the fainter component in 1999 and 2000 is in fact the primary, the correct position angles would be 7°.0 and 3°.1, which agree well with the other observations.

With this assumption, the position angle changed by almost 16° over the observed portion of the orbit, which is not enough to determine reliable orbital elements. Nevertheless, we tried to fit a binary orbit to the observed positions to obtain an estimate of the orbital parameters. The best-fitting orbit has a period of 43 yr, an eccentricity of 0.2, and a system mass of 2.1 $M_\odot$. However, there is an orbital solution that fits nearly equally well, with a period of 151 yr, an eccentricity of 0.7, and a system mass of 2.3 $M_\odot$. These two orbits are depicted in Figure 4, and their orbital elements are listed in Table 4. Furthermore, it is possible to find reasonably good-fitting orbits for all eccentricities between 0 and 0.4, which result in periods in the range 43–100 yr, semimajor axes between 16 and 20 AU, and system masses between 0.9 and 2.1 $M_\odot$. From comparison with the evolutionary tracks in the previous section, one would deduce a system mass of about 1.5–2 $M_\odot$, in agreement with the mass derived from the orbital parameters.

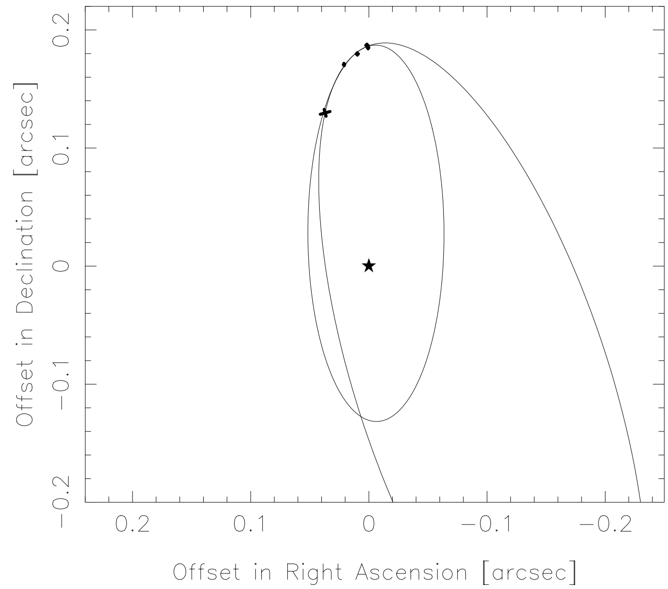

FIG. 4.—Positions of RECX 1B relative to RECX 1A and two possible orbits with eccentricities of 0.2 and 0.7. Note that the position angles given in Köhler (2001a) are off by 90°.

5.3. *The Deficiency of Binaries with Separations above* 0″.3

It is a surprising result that we find two binaries, both with separations of about 0″.2, but not one with a larger separation. Binaries among solar-type main-sequence stars (Duquennoy & Mayor 1991)[4] and most samples of young binaries show a very broad distribution of separations.

Two binaries hardly form a distribution, and therefore it is not easy to make a quantitative statement whether our two binaries could have been drawn from the distribution

[4] Duquennoy & Mayor (1991) give only the period distribution of their sample. To compare their results with the measured separations of our stars, we use the separation distribution of main-sequence stars computed in Köhler (2001b).

TABLE 4
ORBITAL ELEMENTS OF THE TWO BEST SOLUTIONS FOR THE ORBIT OF RECX 1

Parameter	Orbit 1	Orbit 2
a (arcsec)	0.160	0.388
e	0.204	0.700
i (deg)	68.6	72.5
Ω (deg)	89.4	77.9
ω (deg)	212.0	295.8
P (yr)	42.5	150.8
T_0	1985.9	1993.2
a (AU)[a]	15.5	37.6
M_{sys} ($M_\odot$)[a]	2.1	2.3

[a] At a distance of 97 pc.

given by Duquennoy & Mayor (1999) or not. The usual statistical tests to decide if two samples were drawn from the same distribution give no meaningful results. However, the situation is better than it might seem, since we can use the information that there are *no* binaries with separations greater than 0.″3. To gauge whether or not the two "distributions" are different, we divide the range of separations observed in our survey into two logarithmically equal-sized bins, one from 0.″13 to 1.″02 and one from 1.″02 to 8″. At a distance of 97 pc, these bins correspond to 12.6–100 and 100–776 AU. If we observe a sample of 13 stars with the same binary frequency and distribution of separations as observed by Duquennoy & Mayor, we would expect to find 1.8 ± 0.4 binaries with separations between 12.6 and 100 AU, and 1.4 ± 0.3 binaries between 100 and 776 AU. While the number of close binaries agrees with our result for η Cha, we find a significantly lower number of wide binaries. If the number of binaries observed follows a Poisson distribution, the probability of finding no binary if 1.4 are expected is only 23%. Although this might indicate that there is indeed a deficiency of binaries with large separations in η Cha, we cannot fully exclude a random fluctuation due to small number statistics.

6. CONCLUSIONS

We conducted a multiplicity survey of the η Chamaeleontis cluster and find two binaries among 13 cluster members. An additional companion at a larger separation from RECX 1 is probably an unrelated background star.

Our resolved photometry allows us to place the individual components in color-magnitude diagrams and compare them with theoretical evolutionary tracks. This reduces the scatter of the CMD shown in Lawson et al. (2001), where only the total flux of the binary systems was known, and reveals that most stars in η Cha are coeval. The one notable exception is RECX 12, which was suspected to be a binary by Lawson et al. (2001) because of its elevated position in the CMD. We are unable to resolve this star, but we find indications that it might be a binary with a separation smaller than our detection limit.

We observed RECX 1AB at five different occasions in the years 1996–2001. In this time, its position angle changed by almost 16°, and its separation by 0.″05. The part of the orbit covered by these observations is not large enough to compute precise orbital elements, but it is already now possible to conclude that the system mass is about 2 $M_\odot$, in agreement with the results deduced from comparison with evolutionary tracks. With more observations, it should be possible to derive reliable orbital elements of this star within a few years.

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