Detection of non–radial pulsation and faint companion in the symbiotic star CH Cyg

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ABSTRACT

We have detected asymmetry in the symbiotic star CH Cyg through the measurement of precision closure–phase with the IONIC beam combiner, at the IOTA interferometer. The position of the asymmetry changes with time and is correlated with the phase of the 2.1–yr period found in the radial velocity measurements for this star. We can model the time–dependent asymmetry either as the orbit of a low–mass companion around the M giant or as an asymmetric, 20% change in brightness across the M giant. We do not detect a change in the size of the star during a 3 year monitoring period neither with respect to time nor with respect to wavelength. We find a spherical dust–shell with an emission size of 2.2±0.1 D c FWHM around the M giant star. The star to dust flux ratio is estimated to be 11.63±0.3. While the most likely explanation for the 20% change in brightness is non–radial pulsation we argue that a low–mass companion in close orbit could be the physical cause of the pulsation. The combined effect of pulsation and low–mass companion could explain the behaviour revealed by the radial–velocity curves and the time–dependent asymmetry detected in the closure–phase data. If CH Cyg is a typical long secondary period variable then these variations could be explained by the effect of an orbiting low–mass companion on the primary star.

Key words: binaries: symbiotic – stars: imaging – stars: individual: CH Cygni – techniques: high angular resolution – techniques: interferometric.

1 INTRODUCTION

Symbiotic stars are objects presenting combination spectra of a hot ionised nebula and the cool continuum absorption molecular features of a late–type star. Nowadays, symbiotic stars are understood as mass–transfer binaries of short period, from a few to 10 years. The separation can vary from a few AU to slightly more than 10 AU. The symbiotic pair is usually composed of a cool giant star with an accreting compact object, either a white dwarf or a neutron star.

CH Cyg is one of the most studied of symbiotic variables.

The star presents a composite spectrum of a M6–7 giant star during quiescent phase and a hot component blue continuum from 6000 to 9000 K temperature and low excitation line spectrum during the active phase (Deutsch et al. 1974). Webster & Allen (1975) classified the star as an S–type symbiotic with no hot dust, but long term multi–wavelength photometry study of the star (Taranova & Iudin 1988) has shown that hot dust appeared in the system after the 1984 outburst. The dust was modelled as a spherical shell of inner radius of 15 AU by Bogdanov & Taranova (2001) through spectral energy distribution (SED) fitting.

Dyck et al. (1998) measured an angular diameter of 10.4 mas at 2.2 μm for CH Cyg with infrared interferometry, Young et al. (2000) observed CH Cyg with the Cambridge optical aperture synthesis telescope (COAST) in 1999. The obtained visibility and

* Affiliated to Scottish universities physics alliance (SUPA).
table1_log_of_observations_the_iota_3t_telescope_configuration_refers_to_the_location_of_the_a_b_c_telescopes_along_the_ne_se_and_ne_arms

| Date (UT) | Mean JD | Phase | Telescope | λ (μm) | Δλ (μm) | R² | Calibrator names |
|-----------|---------|-------|-----------|--------|---------|----|-----------------|
| 2004Apr23 | 2453119 | 0.40  | IOTA , A35–B15–C10 | 1.51   | 0.090   | α Lyr, α Aql |
| 2004Apr24 | 2453120 | 0.40  | IOTA , A35–B15–C10 | 1.64   | 0.100   | α Lyr, α Aql |
| 2004Apr25 | 2453121 | 0.40  | IOTA , A35–B15–C10 | 1.64   | 0.100   | α Lyr, α Aql |
| 2004Apr26 | 2453122 | 0.40  | IOTA , A35–B15–C10 | 1.78   | 0.090   | α Lyr, α Aql |
| 2004Apr29 | 2453125 | 0.41  | IOTA , A35–B15–C10 | 1.78   | 0.090   | α Lyr, α Aql |
| 2004May01 | 2453127 | 0.41  | IOTA , A35–B15–C10 | 1.78   | 0.090   | α Lyr, α Aql |
| 2004Sep04 | 2453105 | 0.38  | Keck A, Golay mask  | 1.64   | 0.025   | α Lyr |
| 2005Jun06 | 2453528 | 0.94  | IOTA , A35–B15–C10 | 1.66   | 0.300   | α Lyr |
| 2005Jun08 | 2453530 | 0.95  | IOTA , A25–B15–C10 | 1.66   | 0.300   | α Lyr |
| 2006Apr24 | 2453850 | 0.37  | IOTA , A35–B15–C10 | 1.66   | 0.300   | 39 α Lyr, β Her |
| 2006May30 | 2453856 | 0.38  | IOTA , A35–B15–C10 | 1.66   | 0.300   | 39 α Lyr, β Her |
| 2006May01 | 2453857 | 0.38  | IOTA , A35–B15–C10 | 1.66   | 0.300   | 39 α Lyr, β Her |
| 2006May02 | 2453858 | 0.38  | IOTA , A35–B15–C10 | 1.66   | 0.300   | 39 α Lyr, β Her |

Only applicable to the IOTA spectrograph.

CH Cyg shows photometric and radial-velocity variations. In photometry two main periods are found: a small amplitude (0.1 magnitude) ~100 day period (Mikolajewski et al. 1992) likely caused by stellar pulsation and a ~770 day period (Mikolajewski et al. 1992) or ~1 magnitude, ~750 day period (Skopal et al. 2007). These photometric variations are not always detected (Munari et al. 1996) and are not related to the 100-day pulsation period. Hinkle et al. (1993) pointed out that the photometric variations of CH Cyg are far longer than the fundamental pulsation mode for this star, which is a first-overtone pulsator (Mikolajewski et al. 1992). The radial-velocity variations from the literature (Hinkle et al. 1993) show two periods: a 15.6-yr long period and a 2.1-yr (750 days) short period.

Hinkle et al. (1993, 2008) suggested a correlation between the 750/770 days photometric period and the 750 days radial-velocity period. They also remarked that the photometric variations of CH Cyg are similar to those found in long secondary period (LSP) variable stars (Hinkle et al. 2006). This type of variability is found in some semi-regular variables and in about the 25% of the Large Magellanic Cloud (LMC) semi-regular variables. Hinkle et al. (2002) and Wood et al. (2004) found that several semi-regular variables also show spectroscopic behaviour consistent with LSP variability. The cause of the LSP is currently unknown but possible explanations are highlighted in Wood et al. (2004). They conclude that the most likely explanation for LSP variations is a low order non radial pulsation on the outer radiative layers of the giant star.

Wood et al. (1999) also discovered that LSP variables follow a period–luminosity (P–L) relation which he called “sequence D”. Soszyński et al. (2004) noted that Wood sequence-D variables overlap with sequence-E contact binaries, implying that sequence-D is indeed a class of binaries. Soszyński (2007) also found that 5% of LSPs in the LMC present ellipsoidal–like or eclipsing–like modulation that are usually shifted in phase with respect to LSP light curves.

Hinkle et al. (1993) proposed a model where CH Cyg was a triple system with the symbiotic pair in a 2.1-yr orbit. The reasons for having the symbiotic pair on the 2.1-yr orbit were that no known S-type symbiotic star had orbital period larger than 5 years, the 2.1-yr period was too long for a M giant fundamental-mode pulsation and there was weak evidence for a high inclination 15.6-yr orbit. The third star was either regarded as a G–K dwarf (Hinkle et al. 1993) or a M giant (Skopal et al. 1996). The inclination of the 15.6-yr orbit was unknown at the time but was recently inferred from the several eclipses reported in the literature (Mikolajewski et al. 1993; Eyres et al. 2002; Sokoloski & Kenyon 2003; Schmidt et al. 2006) that suggested the 2.1-yr period was caused by a pulsation in the M giant and not by a close binary.

There is controversy on the shape of the possible orbit of the close pair. Hinkle et al. (1993) argued that the asymmetric line profiles could be caused by a M giant star irradiated by a white dwarf. An asymmetric line profile could lead to a false elliptic solution for an orbit obtained from radial velocities. According to Hinkle et al. (1993) the orbit of CH Cyg should be circular due to tidal interaction with the M giant.

Hinkle et al. (2008) re-examined the conclusions of the Hinkle et al. (1993) paper. They concluded that the 2.1-yr velocity variation is consistent with LSP variation and that the white dwarf responsible for the activity in the system is on the 15.6-yr orbit. The 2.1-yr period would be caused either by non-radial pulsation of the star or by a low-mass companion in close orbit to the M giant.

This paper presents the results of infrared interferometric observations performed in 2004–2006 at the infrared optical telescope array (IOTA) (Traub et al. 2004) and at the Keck–1 telescope fitted with an aperture mask. The main aim of this paper is to provide unique observational data that could help to understand the nature of the mysterious 2.1-yr oscillation in radial velocity for this star.
Table 2. Calibrator information.

| Calibrator name | Spectral type | Adopted UD (mas^2) | Reference(s) |
|-----------------|--------------|---------------------|---------------|
| α Lyr           | A0V          | 3.22±0.01           | Absil et al. (2006) |
| β Her           | G7IIIa       | 3.40±0.03           | This work     |
| ρ Ser           | K5III        | 3.28±0.04           | Bordé et al. (2002) |
| α Aql           | A7V          | 3.46±0.04           | van Belle et al. (2001) |

α = milliarcseconds

2 OBSERVATIONS AND DATA REDUCTION

Observations were performed at the IOTA interferometer and at the Keck–1 telescope. IOTA was a long–baseline optical interferometer located at the Smithsonian Institution’s Whipple Observatory on Mount Hopkins, AZ. IOTA operated from 1995–2006, and was used as a testbed for new cutting–edge technologies (Berger et al. 2001; Monnier et al. 2003). IOTA produced a large number of astronomy results over the past few years (Mennesson et al. 2002; Ohnaka et al. 2003; Monnier et al. 2004; Perrin et al. 2004; Kraus et al. 2005; Millan-Gabet et al. 2006; Monnier et al. 2006; Zhao et al. 2007; Kraus et al. 2007; Ragland et al. 2008; Lacour et al. 2008).

Observations performed at the Keck–1 telescope used the near infrared camera (NIRC) and an aperture mask that converted the telescope pupil into a sparse interferometric array of 9.8 m maximum baseline. For detailed discussion of the Keck aperture–mask experiment and scientific rationale see Tuthill et al. (2000).

In Table 1 we present a journal of our observations, listing date, filter and calibrator star. In Table 2, we detail the physical properties of the calibrators. Our H–band data used the IONIC combiner (Berger et al. 2003) with narrow H–band filters at the IOTA interferometer and at the Keck telescope for the observations of 2004, while data was acquired using a standard H–band filter at IOTA for 2005. Data from 2006 used a low–dispersion spectrograph which provided seven spectral channels across the H–band with an R=39. For a description of the spectrograph see Ragland et al. (2003) and Pedretti et al. (2008). First results with the spectrograph were published by Lacour et al. (2008).

For the aperture–masking experiment we refer the readers to the work of Monnier (1999) and Tuthill et al. (2000) for the data–analysis, procedures adopted to extract visibilities and closure–phases in OIFITS format (Pauls et al. 2003).

The data reduction pipeline for the IONIC combiner was described in detail in Monnier et al. (2004). Briefly, reduction of the squared visibilities (V^2) followed the same method explained by Coade Du Foresto et al. (1994). Interferograms were corrected for intensity fluctuations and bias terms from readout noise and photon noise. The power spectrum of each interferogram was calculated in order to measure V^2. A transfer matrix was used to take in account the variable flux ratio for each baseline. The absolute calibration accuracy was studied by Monnier et al. (2004) by observing single stars of known size.

Closure phases for the IONIC combiner were obtained using two independent methods; one was developed by Baldwin et al. (1996) for the Cambridge optical aperture synthesis array (COAST), and the other by Hale et al. (2003) for the infrared spatial interferometer (ISI). In order to measure meaningful closure phase, fringes must at least be present in three baselines and the fringe packets must overlap, to be detected in the same coherence time. The largest error in closure phase offset for a point source was caused by chromaticity in the combiner which limits the absolute precision when source and calibrator are not the same spectral type. Engineering tests performed by Monnier et al. (2004) showed that the closure phase varied systematically by 1.4 ± 0.3° between a cool star of spectral type M3 and a hot B8 star.

The IOTA data pipeline produced visibility and closure phases in OIFITS format, which can be easily imported in imaging or modelling programmes using libraries provided by John Young, for C and Python. A standard 2% systematic error was added in quadrature to the visibility and closure–phase data as in Monnier et al. (2004). Calibrated data in OIFITS format will be made available on request for interested investigators.

3 MODELLING

Wood et al. (2004) conducted a thorough review on the causes of the LSP variations in asymptotic giant branch (AGB) stars. They ruled out several possible models, among which were radial pulsation, companion in close orbit, spots on the star and modulation from an ellipsoidal–shaped AGB star. They concluded that non–radial pulsation was the most likely explanation for LSP. In their recent paper Hinkle et al. (2008) after a thorough review of the literature on CH Cyg applied a similar approach to rule out possible models explaining the 2.1–yr change in radial velocity in CH Cyg. We used our interferometry data to verify some of the hypotheses discussed in these papers. Due to limited uv–plane coverage of the data (see Figure 1), in particular for the 2005 epoch, we could not resort to model–independent imaging of the CH Cyg system. For this reason we used parametric modelling to derive the size of the star, the FWHM size of the dust and the position and distance of the star.

Figure 1. The uv coverage for CH Cyg for 2004 (circles) 2005 (squares) and 2006 (triangles). The shades of grey represent the wavelength of the data points.

1 http://www.mrao.cam.ac.uk/research/OAS/oi_data/oifits.html
2 http://www.astro.ha.umich.edu/~monnier/oi_data/index.html
asymmetries detected in the closure–phase data. For model fitting we used publicly available least–squares minimisation routine.

Our modelling was similar to except that we did not need to model multi–wavelength sizes for the star, since CH Cyg does not change size appreciably with respect to wavelength. We decided to test the following hypothesis to investigate the cause of the LSP variations and to interpret our data: (1) radial pulsation of the star, (2) presence of dust inside the 15.6–yr orbit (3) spots on the star, (4) M giant companion in a 15.6–yr orbit, (5) dwarf companion in a 2.1–yr orbit, (6) non–radial pulsation.

3.1 Radial pulsation and dust

In order to test (1) and (2) a simple model composed of a uniform disc (UD) for the star and a Gaussian disc (GD) for the dust was first attempted in order to obtain a size for the star and for the dust. All data from all epochs were used for this model since, by visual inspection, our visibility points superposed quite well, indicating that the size of the star did not change appreciably outside the error bars of the data, neither with time nor wavelength nor position angle.

Figure 2 shows the result of the fit. The data were smoothed using an azimuthal average due to the otherwise very large number of data points present on the graph. For each bin we used the mean of the original data points weighted by their errors. The error on each new data point was the standard deviation for the bin. The fit was performed on the original and non–smoothed data. Table 3 shows the parameters obtained from the fit. The value of 8.74±0.02 milliarcseconds (from now on mas), for the diameter of the M giant is the most accurate so far thanks to the large amount of data used. This value is close to the value of 7.8±0.6 obtained with infrared interferometry in June 2001 by using a simple UD fit. The errors were derived using bootstrap statistics on the data set. The full–width half maximum size of the Gaussian dust emission was 19.13±0.00 mas or 2.2±0.1 stellar diameters FWHM, showing that hot dust exists close to the M giant.

Table 3. Size of star and size of the dust–shell emission. We used a uniform disc to model the star and a Gaussian disc to model the dust. A model with a spherical dust–emission and a model with an elliptical dust–emission were attempted. The two models produced a very similar reduced χ²

| Size FWHM | Flux ratio | P.A. | Axis ratio | Reduced χ² |
|----------|-----------|------|------------|------------|
| M giant  | dust³     | (M giant/dust) | (°) | (M/m) | |
| 8.74±0.02 | 19.1±1.0  | 11.6±0.3 | 0.0 | 1.0 | 1.3 |
| 8.74±0.02 | 19.2±0.9  | 11.6±0.1 | 103±5 | 1.28±0.01 | 1.2 |

³ Size of the dust emission.

A marginally improved reduced χ² was obtained by fitting an elliptical dust distribution around the star. However the difference in reduced χ² was too small in order to justify an asymmetric model for the dust emission in the near infrared. The parameters from the elliptical dust–emission model are also listed in Table 3.

Thompson et al. [2002] monitored an oxygen–rich and a carbon–rich Mira star measuring the change of angular size with respect to the pulsation cycle at the Palomar testbed interferometer (PTI). We did not detect any such change in CH Cyg. Unfortunately our coverage of the 2.1–yr period was quite limited (basically two points at phase 0.4 and one point at phase 0.9 of the “orbital” period). This coverage is insufficient to completely rule out radial pulsation for this star. However, we notice that Hofmann et al. [2003] obtained a diameter of 7.8±0.6 mas in June 2001, using a simple UD model with three visibility points. Considering the crude UD model used that does not take in consideration the dust shell, this diameter is not very different from our measurement and would indicate that the star did not change diameter with time. Also, radial pulsation was ruled–out by Hinkle et al. [2008] as the cause for secondary period in CH Cyg since the period–luminosity relation for AGB stars (Hughes & Wood [1990]) would produce a period of about 250 days for a K~7.5 star not 770 days.

3.2 Spots on the star

In order to model the closure–phase signal expected from a spotted star, we used an additional uniform disc that could be placed at different position angles and separation from the centre of the UD + GD model representing the M giant and the dust emission. Flux ratios between the M giant and the companion/spot and between the M giant and the dust were allowed to change. The size of the additional UD was also free to change. The three epochs were analysed separately in order to detect asymmetries that would change with the observing epoch. We performed a parameter–space search in an attempt to identify the position of the asymmetry.

We could not find any solution with an unresolved or moderately resolved spot on the surface of the star. All the solutions converged to structure outside the disc of the M giant unless we restricted the flux to 10% or more of the flux of the M giant as done in Section 3.3.

3.3 M giant companion on the 15.6–yr orbit

We tested the hypothesis that the companion is a red giant in the 15.6–yr orbit as discussed in the model proposed by Skopal et al. [1996]. That model was devised to explain the eclipses observed...
Table 4. Orbital positions for the low–mass object.

| Mean JD | Sep (mas) | P.A. (°) | Flux ratio M giant/ dwarf | Flux ratio M giant/ dust | Reduced χ² |
|---------|-----------|----------|--------------------------|-------------------------|------------|
| 2453122.9 | 7 ± 3     | 188 ± 37 | 78 ± 1                   | 9.6 ± 0.4               | 0.9        |
| 2453529.0 | 8 ± 3     | 356 ± 4  | 88 ± 5                   | 18.7 ± 1.0              | 0.2        |
| 2453529.0 | 32 ± 3    | 331 ± 3  | 104 ± 4                  | 18.4 ± 0.8              | 0.3        |
| 2453855.2 | 6 ± 2     | 211 ± 32 | 74 ± 1                   | 14.2 ± 0.4              | 0.9        |

in the 15.6–yr orbit and kept the symbiotic pair in the 2.1–yr orbit, given that there are no known symbiotic stars found on an orbit of period as long as 15.6 yrs. We restricted the flux ratio of the M giant/companion to values around 8.6, as expected in Taranova & Shavrin (2004). The field of view (FOV) of IOTA was limited by the bandwidth of the photometric filter used: FOV = λ²/ΔλB, where λ is the wavelength Δλ is the bandwidth and B is the baseline. For the largest bandwidth used (0.3 μm at 1.65 μm) and a baseline of 38 metres we obtained a minimum FOV of 50 mas. We performed a 50 mas wide search in all our data sets. We did not find any trace of a companion in our best data sets of 2004 and 2006 when using the Taranova flux ratio. A second red giant should have been evident in the data. In particular the Keck telescope aperture–masking experiment should have easily detected a second giant star down to a flux ratio M giant/companion of about 100 (Ireland et al. 2008; Kraus et al. 2008).

3.4 Dwarf companion in a 2.1–yr orbit

We tested the hypothesis of a faint companion orbiting the M giant as in Section 3.2 and Section 3.3. We restricted the flux contribution of the companion to less than 2% of the total flux in order to simulate a large Δm between the M giant and the companion. As a consequence we found asymmetries outside the M star in all three data sets. Figure 4 shows the likelihood maps obtained from the reduced χ² surfaces. The dotted–line ellipses are the errors on the positions of the companion which are quite large in the East–West direction due to the limited uv coverage of the IOTA in that direction.

Table 4 lists the separations, position angles, flux ratios and reduced χ² of the asymmetries for the three epochs. The UD size of the companion converged to a point source for all epochs. The error bars on the parameters were derived from the error ellipses. The 2005 data set converged to two separate solutions: one at 8 mas separation and another 32 mas separation. The second solution was less likely due to a degeneracy caused by the limited amount of data available for the 2005 epoch. We could fit the 2.1–yr elliptical orbit to the 32 mas position, with a χ² of 0.3. The semi-major axis of this orbit was 25.6 ± 0.8 mas which produced a far smaller luminosity and a much shorter distance than expected for this star. For this reason we excluded this solution. We must point out that Balega et al. (2007) detected a faint companion with speckle interferometry in 2004 at 43 ± 1 mas separation and 24.1 ± 2.1° position angle. However we do not believe that our 32 mas position is related to this detection. In fact the Keck telescope aperture–masking experiment should have easily detected a companion down to a flux ratio M giant/companion of about 100 in our 2004 data (Ireland et al. 2008; Kraus et al. 2008) but such detection did not happen.

In order to investigate the hypotheses that the detected asymmetries were the signature of a faint companion in a 2.1–yr orbit we attempted orbit fits to the astrometric positions derived from the IOTA closure–phase data using infrared radial–velocity orbital solutions from Hinkle et al. (2008). We attempted orbital fits using a circular orbit (Fekel 2008) which was discarded in Hinkle et al. (2008) due to the large residuals in the orbit fit. We also used the elliptical orbit solution from Hinkle et al. (2008). We obtained a reduced χ² of 0.1 for the circular orbit and a reduced χ² of 0.3 for the elliptical orbit. Such small reduced χ² values are possible given the small number of degrees of freedom (3 from the 6 data points and 3 free parameters) and the quite large error bars on the astrometric positions. The obtained orbits are shown in Figure 5.

The combined orbital parameters from radial velocity and interferometry and some derived parameters are shown in Table 5. The first part of the table lists the orbital parameters from Hinkle et al. (2008) and Fekel (2008). The errors on the parameters obtained from interferometry were derived using Monte Carlo simulations.

3.5 Non–radial pulsation

Although we could not obtain acceptable reduced χ² from the “spots on the star” model we managed to obtain reasonably good fits in simulations of large asymmetries on the star. We used low–order spherical harmonics to simulate large flux variations (up to 20%) across the star. Such a dramatic brightness change could simulate the closure phase signal of CH Cyg but seemed an unlikely explanation even in term of non radial pulsation: we are not aware of any physical mechanism that could produce such a dramatic change of brightness across a star. Figure 5 shows the models and the corresponding fits of visibility and closure phase. The reduced χ² was reasonably close to the dwarf–companion model. The asymmetry appears to rotate with the 2.1–yr period.

4 DISCUSSION

Hinkle et al. (2008) restricted the possible explanation for the 2.1–yr secondary period of CH Cyg to a low–order g–mode non–radial pulsation of the M giant or a to low–mass companion (0.2 M⊙) in close orbit to the M giant. In this model the companion responsible for the activity is on the 15.6–yr orbit.

According to Hinkle et al. (2008) a 0.2 M⊙ companion would have a temperature of about 3200K and would be spectroscopically indistinguishable from the M giant. Since CH Cyg is single–lined binary/triple star the masses of the components cannot be derived directly. We can however test the derived parameters against the published literature, assuming the mass of one of the components. Table 5 shows the change of the derived parameters for different values of the mass of the companion. M1 is the mass of the M giant in solar masses, R1 the radius in solar radii, L1 the luminosity in solar luminosities. The semi–major axis “a” of the orbit in physical units of AU was obtained using Kepler’s law. D is the distance in parsecs. The table is divided in two parts, one concerned with the circular orbital solution and one with the elliptical solution.

The mass of 2 M⊙ from Hinkle et al. (2008), a luminosity of 6900 L⊙ from Biller et al. (2008) and a radius of 280 ± 65 R⊙ obtained by Schmid et al. (2004) through infrared spectroscopy were used to restrict the solutions listed in Table 5. A value of 0.32 M⊙ for the low–mass companion yielded a mass of 2 M⊙, a radius of 250 R⊙ and a luminosity of 6517 L⊙ for the M giant, very close to the values from the literature.

Also, the distance obtained from the size of the circular orbit derived using Kepler’s law and the apparent size of the orbit.

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Figure 3. Binary–star search in $\chi^2$ space. A simple binary-star model was fitted to the visibility and closure–phase data from different epochs. The M giant was kept at the centre of the field while the companion was placed in all possible positions of a $40 \times 40$ mas square grid. A reduced $\chi^2$ value was obtained for each position and the values recorded on a two-dimensional array. Left column shows a likelihood surfaces derived from the $\chi^2$ arrays for our 2004, 2005a and 2005b (non–unique solutions) and 2006 data. The positions of the asymmetries are encoded in the likelihood map. The white crosses represent the positions of the asymmetry and the white ellipses encode the uncertainty of the position. The centre column shows data–versus–model plots for closure phase. The right column shows visibility–versus–spatial–frequency plots (filled circles) with superposed points derived from the model (open diamonds). Note that the high density of data points makes it very hard to distinguish between filled circles and open diamonds. We observed that the closure phase flipped sign between 2004 and 2005 and between 2005 and 2006 meaning that the the detected asymmetry was in the opposite direction in 2005.
Infrared interferometry of CH Cyg

Figure 4. The astrometric orbit of CH Cyg. The plots show an elliptical orbit fit (left) and a circular orbit fit (right). Superposed to the orbits are a uniform disc representing the star and a Gaussian disc representing the dust emission in the system. The flux contribution from the dust was exaggerated to render the dust extent visible in the picture. The diamonds are the expected positions of the companion relative to the M giant, according to the ephemeris. The observed positions of the secondary component are marked with error ellipses (dotted line) centred around a star symbol. The triangles are the expected positions of the companion during the observations at the COAST interferometer. The dashed–line ellipses represent an elliptical model of CH Cyg from Young et al. (2000). The major axis of the ellipses is also shown to better appreciate the orientation of the ellipses.

Table 5. Orbital parameters of the possible low–mass object.

| Parameters       | Circular solution | Elliptical solution |
|------------------|-------------------|--------------------|
| $P$ (days)       | 749.8±2.3         | 750.1±1.3          |
| $T0$ (HJD)       | 2446823.2±7.7     | 2447293.5±12.9     |
| $\omega$ (°)     | 0.0               | 229.5±7.7          |
| $e$              | 0.0               | 0.330±0.041        |
| $K$ (Km s$^{-1}$) | 2.87±0.13         | 2.87±0.13          |
| $\gamma$ (Km s$^{-1}$) | -59.93±0.10     | -59.91±0.09        |
| $a \sin i$ (Km)  | 2.96x10$^7$±0.29x10$^7$ | 2.79x10$^7$±1.23x10$^7$ |
| $f(m)$ (M$_{\odot}$) | 0.00018±0.0002 | 0.00015±0.0002 |

Interferometry

| Parameters       |        |
|------------------|--------|
| $i$ (°)          | 138±10 |
| $\Omega$ (°)     | 347±7  |
| $a$ (mas)        | 7.1±0.3| 6.3±0.3|

in milliarcseconds, was 296 pc, comparable within errors to the 244±45 pc distance obtained from the revisited data reduction of the Hipparcos parallax (van Leeuwen 2007).

Soszynski et al. (2004) found that Wood’s sequence–D variables are a continuation of sequence–E ellipsoidal variables. Soszyński et al. (2007) require that the ratio between the radius of the star and the semi–major axis of the orbit should be $R/a \sim 0.4$ for the binary explanation of the LSP (Equation 5 in Soszynski et al. (2007)). For our circular orbit solution the ratio derived by the angular diameter of the star and the semi–major axis of the hypothetical orbit is 0.6, ~50% larger than the required value.

Soszynski (2007) also proposed a model where the LSP variation are caused by mass loss from the giant to the low–mass companion. Since we detected hot–dust emission inside the possible 2.1–yr orbit we cannot exclude that LSP photometric variation are caused by dust trailing the low–mass companion. There have been claims of eclipses in the 2.1–yr orbit of CH Cyg (Skopal et al. 1996; Iijima1998). The inclination of the circular orbit obtained from the interferometric data would prevent eclipses but if the dust is clumpy and is trailing the companion it could be responsible for occasional photometric variations and could simulate eclipses.

Another clue in favour of the low–mass companion explanation for the LSP variation of CH Cyg comes from the independent interferometric observations of Young et al. (2000) at the wavelength of 905 nm. The visibility and closure–phase data from the COAST interferometer were modelled by an elliptical, limb–darkened star (parameters from that model are reproduced in Table7). Figure 4 shows the astrometric orbit of CH Cyg for the elliptical and circular orbit solution superposed to the models from Young et al. (2000). Interestingly the minor axis of the two ellipses is very close to the radius of the M giant obtained from our model, while the major axis intersects the predicted orbital position of the companion on the circular orbit. The major axis of the ellipses did not intersect the orbital positions of the companion on the elliptical orbit. Also, our elliptical orbit fit to our astrometric positions had a $\chi^2$ 3–times worse than the circular orbit fit.

According to Hinkle et al. (2008) the most powerful argument against the close–binary explanation of LSP variation in CH Cyg is
the shape of the radial–velocity curve: the most likely orbit for the low–mass companion would be elliptical due to the large radial–velocity residuals obtained from fitting a circular orbit. On the other hand Hinkle et al. (2008) derived a mass of 2.0 M⊙ for the M star, based on evolutionary arguments and argued that the Roche lobe for a 2 M⊙–0.2 M⊙ binary would constantly change from \((1 + e)a\) at apoastron to \((1 - e)a\) at periastron for an elliptical orbit. A 280 R⊙ giant would fill the Roche lobe at each periastron passage generating large mass loss. We argue that distortion by proximity effect (Eaton 2008) could also change the shape of the radial velocity curve and therefore the circular orbit solution cannot be eliminated on the basis of this argument.

Hinkle et al. (2008) argue that non–radial pulsation could also reproduce the observed radial velocities and photometric variation of CH Cyg. The problem with the non radial pulsation argument is that low–order g modes are evanescent in convective regions and there is no known physical mechanism that could explain the non–radial pulsation for M giant stars where radiative transfer is mostly...
may be due to tidal interaction of the low–mass companion with the pulsation of the star. This could explain the residuals found in fitting the combination of movement of the low–mass companion and non–radial pulsation and circularising binary orbits. Ivanov & Papaloizou (2004) studied tides in fully convective stars. They came to the conclusion that resonant tides may be possible in fully convective stars.

Late type stars turbulence is very efficient in damping these oscillations but can also cause non–radial g–mode resonant oscillations. In late type stars turbulence is very efficient in damping these oscillations and circularising binary orbits. Ivanov & Papaloizou (2004) studied tides in fully convective stars. They came to the conclusion that resonant tides may be possible in fully convective stars.

CH Cyg is a very complex object. If it is a triple system the interactions of the companions with the M star could be very complex. The signature in the radial velocity could be caused by a companion in close orbit around the M giant and/or a low mass companion in close orbit to the M giant. While the most likely explanation for the change in brightness can be a non–radial pulsation we argue that a low–mass companion in close orbit could be the physical cause of the pulsation. The combined effect of pulsation and low–mass companion in close orbit to the M giant could explain the behaviour of the radial–velocity curves and the asymmetries detected in the closure–phase data. If CH Cyg is a typical long secondary period variable then LSP variations could be explained by an orbiting low–mass companion on the primary star.

5 CONCLUSIONS

We have presented simple models in order to explain the asymmetries detected through infrared interferometry in the S-type symbiotic star CH Cyg. We do not detect significant change of angular size (8.74±0.02 mas) for the M giant over a 3 year period, rendering radial pulsation a less likely explanation for the 2.1–yr variability in radial velocity data. We find a spherical hot dust–shell with an emission size of 2.2±0.1 D, FWHM around the M giant star which could be responsible for some of the reported short–period eclipses. We find correlation between the 2.1–yr variability and the variation in our closure phase. We model the closure phase as a large change in brightness across the M giant and/or a low mass companion in close orbit around the star. While the most likely explanation for the change in brightness can be a non–radial pulsation we argue that a low–mass companion in close orbit could be the physical cause of the pulsation. The combined effect of pulsation and low–mass companion in close orbit to the M giant could explain the behaviour of the radial–velocity curves and the asymmetries detected in the closure–phase data. If CH Cyg is a typical long secondary period variable then LSP variations could be explained by the effect of an orbiting low–mass companion on the primary star.

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REFERENCES

Absil O., di Folco E., Mérand A., Augereau J.-C., Coudé Du Foresto V., Aufdenberg J. P., Kervella P., Ridgway S. T., Berger D. H., Ten Brummelaar T. A., Sturmann J., Sturmann L., Turner N. H., McAlister H. A., 2006, A&A, 452, 237
Baldwin J. E., Beckett M. G., Boysen R. C., Burns D., Buscher D. F., Cox G. C., Haniff C. A., Mackay C. D., Nightingale N. S., Rogers J., Scheuer P. A. G., Scott T. R., Tuthill P. G., Warner P. J., Wilson D. M. A., Wilson R. W., 1996, A&A, 306, L13+
Baloga I., Balaga Y. Y., Maksimov A. F., Malogolovets E. V., Rastegaev D. A., Shkhusheva Z. U., Weigelt G., 2007, Astrophysical Bulletin, 62, 339
Berger J. P., Hauenerau P., Kern P., Perrat K., Malbet F., Schanne I., Severi M., Millan-Gabet R., Traub W., 2001, A&A, 376, L31

Table 6. Derived red giant parameters as a function of the faint companion’s mass.

| M2 (M⊙) | 0.1 | 0.2 | 0.3 | 0.4 | 0.5 | 0.6 |
|---------|-----|-----|-----|-----|-----|-----|
| Circular orbit |
| M1 (M⊙) | 0.3 | 0.9 | 1.8 | 2.8 | 3.9 | 5.2 |
| R1 (R⊙) | 156 | 221 | 270 | 312 | 349 | 382 |
| L1 (L⊙) | 2037 | 4073 | 6110 | 8146 | 10183 | 12219 |
| a (AU) | 1.2 | 1.7 | 2.0 | 2.3 | 2.6 | 2.9 |
| D (pc) | 166 | 235 | 288 | 332 | 371 | 407 |

| Elliptical orbit |
| M1 (M⊙) | 0.2 | 0.7 | 1.4 | 2.2 | 3.2 | 4.2 |
| R1 (R⊙) | 165 | 233 | 285 | 330 | 369 | 404 |
| L1 (L⊙) | 2267 | 4534 | 6801 | 9068 | 11335 | 13601 |
| a (AU) | 1.5 | 1.6 | 1.9 | 2.2 | 2.5 | 2.7 |
| D (pc) | 143 | 248 | 304 | 351 | 392 | 430 |

Table 7. Elliptical star model parameters from Young et al. (2000).

| Epoch | Major axis (mas) | Axial ratio | P.A. (°) |
|-------|-----------------|-------------|---------|
| 99/08 | 11.5 ±0.2       | 0.84 ±0.05  | 126±9   |
| 99/09 | 11.2 ±0.2       | 0.79 ±0.03  | 136±5   |

convective. As we show in Figure 5, an asymmetric brightness distribution on the surface of the star could also reproduce our observed closure–phase signature. The flux variation across the star must be very large (20%) in order to explain the closure–phase results and we are not aware of any physical mechanism that could produce such a dramatic change of brightness across a star.

Close encounter with another object can produce non–radial oscillations on a fluid star through tides according to Eriguchi (1990). Circularisation of early–type main sequence binaries are also known to cause non–radial g–mode resonant oscillations. In late type stars turbulence is very efficient in damping these oscillation and circularising binary orbits. Ivanov & Papaloizou (2004) studied tides in fully convective stars. They came to the conclusion that resonant tides may be possible in fully convective stars.

CH Cyg is a very complex object. If it is a triple system the interactions of the companions with the M star could be very complex. The signature in the radial velocity could be caused by a combination of movement of the low–mass companion and non–radial pulsation of the star. This could explain the residuals found in fitting a circular orbit to the radial–velocity data. The non–radial pulsation may be due to tidal interaction of the low–mass companion with the M giant. Such interaction would also cause rapid circularisation of the orbit for the low–mass companion.

It is not clear what the timescale for the circularisation of the orbit and the dissipation of the non–radial pulsation would be. If the dissipation of the non–radial pulsation by convective turbulence is efficient and the timescale for circularisation short it is hard to explain why at least 25% of stars in globular clusters show LSP variations. We suggest that in globular clusters interactions with low–mass companions could be more frequent than expected. LSP variations then would be caused by non–radial pulsations excited by orbital capture of a companion or circularisation of an elliptical orbit.
