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UNUSUAL QUADRUPLE SYSTEM ξ TAU

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Abstract. A premilinary analysis of spectral, photometric and interferometric observations of the triple subsystem of a hierarchical quadruple system ξ Tau is presented. The triple system consists of a close eclipsing binary ($P^{\rm A} = 7\overset{\rm d}{.}146651$), revolving around a common centre of gravity with a distant tertiary ($P^{\rm B} = 145\overset{\rm d}{.}131$). All three stars have comparable brightness: the eclipsing pair is formed by two slowly rotating A stars while the tertiary is a rapidly rotating B star. The outer orbit is eccentric ($e^{\rm B} = 0.20 \pm 0.15$). Available radial velocities indicate an apsidal advance of the outer orbit with period $P^{B}_{\rm APS} \approx 120$ yrs, while the theoretically predicted apsidal period $P^{\rm B}_{\rm APS} \geq 170$ yrs. The results from different observing techniques are mutually confronted in order to test their limitations.

Key words: stars:binary stars, stars:hot stars

1. Introduction

ξ Tau (2 Tau, HD 21364, HIP 16083, HR 1038) is a hierarchical quadruple system, consisting of the sharp-lined A stars, undergoing binary eclipses, a more distant broad-lined B star and a much more distant and faint F star. Here, we shall denote the components as follows: C (F–type), B (B–type), Aa, Ab (A–type) and the orbits: C (F–type), B (B–type), A (A–type). The visual magnitude of ξ Tau ($V = 3\overset{\rm m}{.}72$) and its declination $9°44'$ make it an easy target for a wide range of instruments and observational techniques. The binary nature of the system was discovered by Campbell (1909). The outermost orbit C was resolved via speckle–interferometry by Mason et al. (1999). All speckle–interferometric observations of the system were analysed by Rica Romero (2010), who found an orbital period $P_{\rm C} = 52(15)$ yrs. The orbital elements of the triple subsystem were published by Bolton and Grunhut (2007) in a conference abstract. The Hipparcos parallax of the system is $p = 15.6 \pm 1.04$ (van Leeuwen, 2007a,b). As we were unable to detect either spectral or light variations of the distant and faint F component, we do not deal with orbit C in this study.

2. Observation and data reduction

We have collected rich series of spectroscopic, photometric and interferometric observations spanning over last two decades.

2.1. SPECTROSCOPY

The 131 electronic slit spectra cover time interval RJD = 49300–55971[1]. They were secured at three observatories: 1) Ondřejov, Czech Republic(OND), 2) David Dunlap, Canada (DDO), and 3) Observatório do Instituto Geográfico do Exército, Portugal. We also use radial–velocities (RVs hereafter) measured on 137 DDO photographic spectra (RJD = 40921–42120) by one of us (C.T. Bolton). Of these, 97 RVs were measured on the He I 4026Å line and have a poor quality.

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[1] RJD = JD - 2400000

Spectral lines of all three components are visible in the spectra. We studied the Hγ, Hβ, and Hα Balmer lines and stronger metallic lines, in which the contribution of the A–type stars is dominant. (Mg II 4481 Å, Si II 6347 Å and Si II 6371 Å). The B–type component contributes of about 60 % of the total flux in the optical region and its spectral lines are rotationally broadened. The spectral lines of both A–type stars are sharp and very similar to each other.

2.2. PHOTOMETRY

Altogether, 1786 *UBV* observations (spanning RJD = 54116–55956) were secured at three observatories: 1) Hvar Observatory, Croatia, 2) South African Astronomical Observatory, South Africa, and 3) Villanova APT, USA. We also used 69 Hipparcos H_p observations (Perryman and ESA, 1997) spanning RJD = 55883–55956. These were transformed to them Johnson V following Harmanec (1998). The light curve, which is shown in Fig. 3.2., of the system system shows shallow and narrow minima, which almost do not differ from each other.

2.3. SPECTRO–INTERFEROMETRY

The system was observed with the NOI (earlier NPOI) interferometer between 1991 and 2012, the bulk of observations being taken during the last decade, and with the VEGA/CHARA spectro-interferometer in 2011 and 2012.[2]

3. Data analysis and preliminary results

3.1. ORBITAL SOLUTION

The RVs were measured with two techniques: 1) Via a manual comparison of the direct and flipped line profile in the program SPEFO[3], and 2) using an automatic comparison of suitably chosen synthetic and observed spectra. They were then divided into three subsets well–separated in time, for which the orbital solutions were derived separately. Elements by Bolton and Grunhut (2007) were used as an initial estimate. The orbital period of the inner

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[2] Only 2011 being reported here.

[3] Written by Dr. J. Horn and further developed by Dr. P. Škoda and Mr. J. Krpata.

orbit P^{A} was kept fixed at the value given by light curve solution (see below). We used program FOTEL developed by Hadrava (2004a) for the task. The results revealed presence of apsidal motion of the orbit B with a period of ≈ 120 yrs. The secular rise of the longitude of periastron ω^{B} is shown in Fig. 3.1..

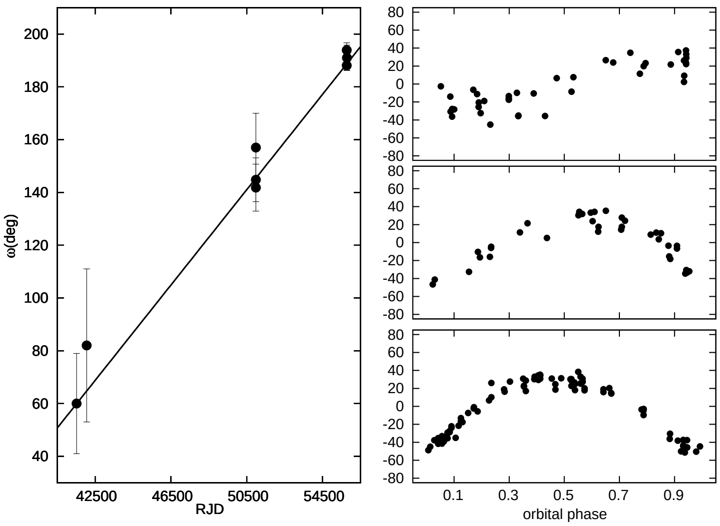

Figure 1: Evolution of orbit B. *Left panel:* A secular increase of the longitude of periastron ω^{B} as found from the orbital solution for the three data subsets. The black line is a linear fit. *Right panels:* The RV curves of the B–type tertiary for the three subsets: *top panel:* RJD 41998–42120, *middle panel:* RJD 49300–52670, *bottom panel:* RJD 55561–55971. The ordinate in all 3 panels is in km s^{-1}.

The spectra disentangling program KOREL (Hadrava, 2004b) was used to the final orbital solution and the corresponding orbital elements are in Tab. 3.1.. The disentangled component spectra are in Fig. 3.1..

3.2. LIGHT-CURVE SOLUTION

We used the program PHOEBE (Prša and Zwitter, 2005) to this task. The limb-darkening coefficients were taken from Claret (2000) and the semimajor axis and the mass ratio following from the KOREL orbital elements were kept fixed. The light contribution from the B–type star had to be considered

Table I: The KOREL orbital solution, where P_{S} is the sidereal orbital period, P_{An} anomalistic orbital period, T_{P} the epoch of periastron, T_{min} the epoch of the RV minimum, e the eccentricity, ω the longitude of periastron, K_1 the semiamplitude, and q the mass ratio.

Element	Outer orbit (B)	Inner orbit (A)
P_{An} (d)	145.6030 ± 0.010	–
P_{S} (d)	145.1378 ± 0.010	7.146651 ± 0.000010
T_{P} (RJD)	55755.0418 ± 0.0100	48299.0758 ± 0.0010
e	0.20 ± 0.15	0.0 ± 0.05
ω (°)	188.5 ± 5.0	–
$\mathrm{d}\omega/\mathrm{dt}$ ($^\circ\,\mathrm{d}^{-1}$)	0.0079	–
K_1 ($\mathrm{km\,s^{-1}}$)	34.91 ± 5.0	89.1 ± 10.0
q	1.09 ± 0.40	0.96 ± 0.10

as the third light, its relative luminosity in the V band being $L_{\mathrm{r}}^{\mathrm{V}} = 0.60$. As the secondary minimum occurs a bit earlier that a half of the period after the primary one, we had to allow for a small orbital eccentricity. The elements of the solution are in Tab. 3.2..

Table II: Light curve solution.

Orbital properties		
Parameters	Values	
P^{A} (d)	7.146656 ± 0.000020	
$T^{\mathrm{A}}_{\mathrm{min}}$ (RJD)	48302.6371 ± 0.0010	
i^{A} (°)	86 ± 1	
e^{A}	0.05 ± 0.03	
a^{A} ($\mathrm{R}_\odot$)	25.79	
Properties of the close binary components		
Parameters	Aa	Ab
r ($\mathrm{R}_\odot$)	1.7 ± 0.2	2.1 ± 0.2
T_{eff} (K)	9450 ± 200	9300(fixed)
$L_{\mathrm{r}}^{\mathrm{V}}$	0.23 ± 0.02	0.17 ± 0.02

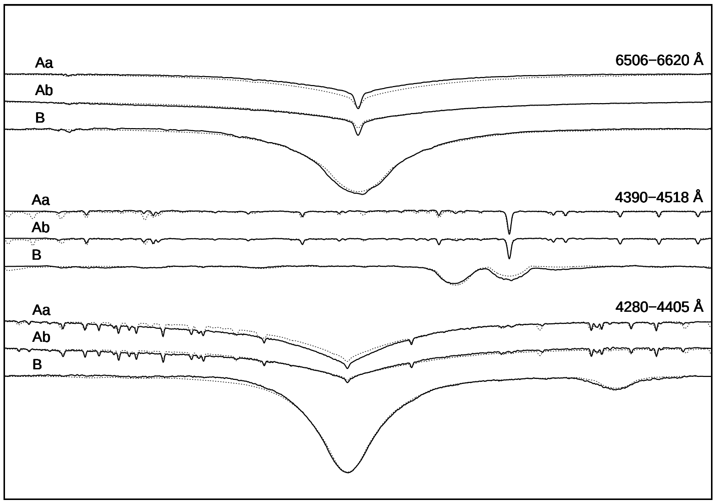

Figure 2: Spectra of the triple subsystem components obtained via disentangling (full line) and synthetic spectra fitted to the disentangled (dotted line). The spectral region covered with a set of spectra is given on the right side of the figure, above each set.

3.3. Interferometric solution

As already mentioned, ξ Tau has been observed with two interferometers. The NOI instrument is unable to resolve the orbit A with the currently available baselines. Only the outer orbit B was resolved. The VEGA/CHARA is capable of resolving the inner system. The results of an astrometric fit to measured positions on the plane of the sky with each instrument are listed in Tab. III.

3.4. Comparison of observed and synthetic spectra

We have used a program, which is being developed by JN. It interpolates in the grids of synthetic spectra and compares them to observed ones in order to find the best match. The elements, which can be optimized, are: the effective temperature $T_{\rm eff}$, logarithm of gravitational acceleration $\log(g)$, the projected rotational velocity $v_{\rm R}\sin i$, relative luminosity $L_{\rm R}$, and radial velocities of the components $RV_{\rm i}$. The grids of synthetic spectra by Lanz and

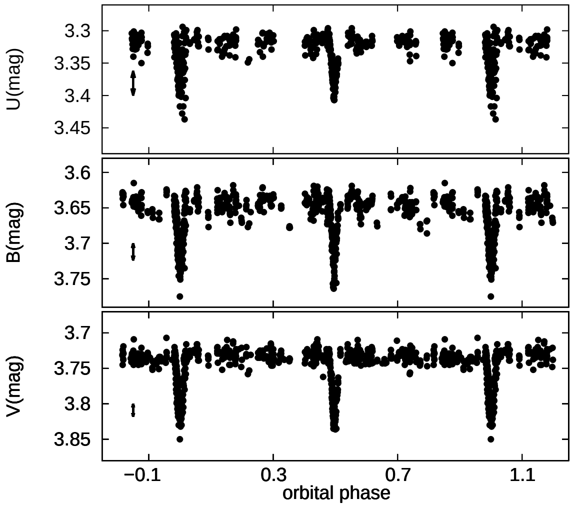

Figure 3: ξ Tau *UBV* light curves *top panel: U* filter, *middle panel: B* filter, *bottom panel: V* filter. Data sources (number of observations): Hvar Observatory(1308), SAAO(76), Hipparcos satellite(69), Villanova APT(401). Upper limit of absolute error of one observation is denoted with an arrow.

Table III: List of the best–fitting interferometric orbital elements. i inclination, Ω ascending node length, e eccentricity, ω periastron length, a angular size of the semimajor axis. *Values of Ω + 180 ° are possible.

	Instrument		
Element	VEGA/CHARA		NOI
E(RJD)	55755.04		53710.9
	Inner Orbit (A)	Outer Orbit (B)	Outer Orbit (B)
i (°)	97.5 ± 5.0	85.0 ± 4.0	87.2
Ω (°)*	350.5 ± 4.0	329.2 ± 2.0	148.6
e	–	0.24 ± 0.04	0.214
ω (°)	–	182.0 ± 5.0	157.6
a (mas)	–	15.5 ± 0.4	16.1

Hubeny (2003, 2007), and Palacios et al. (2010) were used. The best–fitting synthetic spectra are shown in Fig. 3.1. and the corresponding optimal elements are in Tab. 4.1..

4. Discussion

4.1. PROPERTIES OF THE SYSTEM

The estimated precision of the RV measurements of: 1) A–type stars is $\approx 2\,\mathrm{km\,s^{-1}}$, 2) B–type star is $\approx\ 5\,\mathrm{km\,s^{-1}}$. A good phase coverage for both orbital periods led to reliable RV-curve solutions with FOTEL (giving the rms error of 1 observation $\leq 7\,\mathrm{km\,s^{-1}}$). The FOTEL orbital elements provided good initial values for ther final solution with KOREL. We mapped χ^2 around the minimum of the sum of squares found in order to get estimates of the uncertainty of the elements. No really detailed error analysis has been carried out, however, and the errors given in the Tab. 3.1. were estimated on basis of the above–mentioned maps.

Table IV: Result of the synthetic spectra fitting to the observed spectra. T_{eff} effective temperature, $\log(g)$ logarithm of gravitational acceleration, $v_{\mathrm{R}}\sin i$, projected rotational velocity, L_{r} relative luminosity, RV radial velocity and Z metallicity. $\Delta\lambda \epsilon$ [4380, 4500] Å region was fitted.

Parameter	System component		
	B	Aa	Ab
T_{eff} (K)	15100 ± 200	9400 ± 500	9200 ± 500
$\log(g)_{[cgs]}$	4.3 ± 0.1	4.2(fixed)	4.2(fixed)
$v_{\mathrm{R}}\sin i\,(\mathrm{km\,s^{-1}})$	246 ± 10	33 ± 2	34 ± 2
L_{r}	0.67 ± 0.02	0.14 ± 0.02	0.13 ± 0.02
$RV_{\gamma}\,(\mathrm{km\,s^{-1}})$	2.4 ± 5.0	7.7 ± 5.0	6.9 ± 5.0
$Z(\mathrm{Z}_{\odot})$	2(fixed)	2(fixed)	2(fixed)

The light curve solution show high degeneracy in the diameters of stars. This is due to very shallow and almost identical eclipse minima. The light curve solution also indicates a small eccentricity of orbit A (0.03–0.06). The mutual interaction between the close binary A and tertiary should also cause nodal motion. If the orbits are not coplanar, the depths of the eclipses should vary with time. Comparing the observations from two seasons only, we cannot firmly confirm such an effect.

The interferometric solutions from NPOI and VEGA/CHARA agree with each other.

The fit of the synthetic spectra to the observed ones is affected by two systematic errors. First, the current version of the program does not interpolate in metallicity. Second, the program assumes a wavelength-independent relative luminosities of component stars. This means one should not fit long spectral intervals in one program run.

4.2. APSIDAL MOTION

At present, we are confronted with some controversy concerning the apsidal advance of orbit B. If real – as the analysis of 3 local subsets of RVs strongly suggests – it is probably caused by a dynamical interaction between the close binary and the distant tertiary. The semimajor axis of the orbit B $a \approx 250\,\mathrm{R}_\odot$ and a relatively low eccentricity $e \approx 0.2$ exclude the possibility that the apsidal advance would be caused by the stellar internal structure. We estimated the periods of apsidal motion $P_\mathrm{B}^\mathrm{APS} \epsilon\ [170, 400]$ yr and nodal motion $P^\mathrm{NOD} \epsilon\ [18, 22]$ yr with the help of formulæ derived by Soderhjelm (1975) and by a direct integration of Lagrange equations. Both values depend heavily on the angle between the orbital planes. The observed apsidal-motion period does not fit in the predicted interval, which indicates some unresolved discrepancy in our model of the system.

The apsidal motion was *not* confirmed by an analysis of NOI interferometric observations. Their optimal fit shows orbit with no apsidal motion and an orbital period $P_\mathrm{B} = 145\overset{\mathrm{d}}{.}65$ (see also Hummel in this Volume). At present, it is not possible to check on the apsidal motion in the VEGA/CHARA data, since they only cover a short interval (2011 – 2012). The discrepancy can only be resolved by continuing observations of both types.

5. Future plans and expectations

The ultimate goal of our effort will be the determination of very accurate component masses and radii and of dynamical properties and possible evolution of the system. We plan to obtain a high-precision light curve of the eclipsing pair with the MOST satellite, and continue observations with the VEGA/CHARA interferometer as well as ground-based photometric and spectroscopic observations.

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