Investigating multiplicity of binary stars and the nature of substellar companions with the Greek 2.3m Aristarchos telescope

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THE PROGRAM
Follow-up observing program initiated in 2013 with the 2.3 m Aristarchos telescope at Helmos Observatory, Greece,
THE GOAL

Investigate the nature of interesting W UMa type eclipsing binaries from Kepler field

- to verify the Kepler classification
- to construct complete multi-passband light curves
- to determine the spectral type with low resolution spectroscopy
- to model KIC systems using state of the art techniques
- to parameterize the morphology and derive absolute parameters
- to construct O-C diagrams
- to investigate the presence of third body
- to study their evolutionary stage.
Selection of targets

interesting W UMa type eclipsing binaries (EBs) from Kepler field with periods < 0.45 d and $K_p$ (mag) =12.6-16 mag.

<table>
<thead>
<tr>
<th>ID</th>
<th>RAJ2000</th>
<th>DecJ2000</th>
<th>Kp (mag)</th>
<th>Per(d)</th>
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<td>18 50 52.37</td>
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<td>KIC4563150</td>
<td>19 28 26.8</td>
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<td>0.274729</td>
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<tr>
<td>KIC11246163</td>
<td>19 31 29.9</td>
<td>+48 59 02.4</td>
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</tr>
<tr>
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<tr>
<td>KIC8108785</td>
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<td>+43 55 32.3</td>
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</tr>
</tbody>
</table>

- First estimation of period is given in *Prsa et al. 2011*
- Some of the targets have interesting ETV (quadratic, cyclic variations) (*Conroy et al. 2014*) or O'Connell effect
First multiband photometric observations

• Full BVRI light curves are covered

High–quality BVRI light curves were obtained with the 2.3 m Ritchey–Chretien Aristarchos telescope (f/8) at the Helmos Observatory in Greece on 4 observing runs (~20 nights during July 2013 - August 2013-August 2014-July 2015).

The observations were taken with a 1024×1024 SITe CCD detector consisting of 24 μm² pixels. The field of view and image scale were 5 ×5 arcmin² and 0.28 arcsec pixel⁻¹, respectively.
A fully automated pipeline for data reduction and analysis (IRAF, PHOT, Astrometry.net)
Light curve modeling of EBs

Data

Binary

Phoebe 1.0 (Wilson-Devinney)

light curve

radial velocity curve

Model

Observables

Simplex

DC

Gradient
Light curve modeling of EBs

- Circular orbits
- PHOEBE 1 “Overcontact not in thermal contact"
- The initial models were constructed using \( q = \frac{M_2}{M_1} \) from EBAI results (Prša et al: 2011, Slawson et al: 2011) and Teff (Huber et al: 2014) These were kept fixed during the fitting procedure
- Fitting with PHOEBE 0.31 scripter in order to conserve \( \alpha \sin i \) and/or B-V color index, setting multiple subsets (MMS Wilson & Biermann 1976).

Methods: Searching for global solution and uncertainties

Method 1: Using Heuristic Scanning (HS) with parameter kicking to explore the parameter hyperspace (Prsa & Zwitter, 2005) as described in Christopoulou & Papageorgiou 2015a, Papageorgiou et al, 2015b
Method 2: Genetic Algorithm-based numerical optimization technique inspired from the biological process of evolution by means of **natural selection** (Metcalfe 1999, 2000)

- Set parameter ranges

- Generate a set of models (trial solutions) (“population”) randomly according to their limits

  1) Calculate CFV from the model (PHOEBE-script) (“fitness”)

  2) Accept the best set of parameters from the list according to minimum CFV and propagate to next generation.

  3) Select the pairs of solutions according to their fitting (“parents”)

  4) Breed the solutions selected in (3) and produce two new by applying crossover and mutation (“offspring”)

  5) Check if the models are physically feasible and propagate to next generation

  6) Go to 1

Evolve the initial list and generate new generations.
Methods: Modeling the light curves (cont.)

\[ X_1, Y_1, X_2, Y_2 \] are the parameters derived from \( S_1 \) and \( S_2 \) solutions

**Step 1: Crossover**

\[ X_1 = 4.8563, Y_1 = 8.2543 \rightarrow 4856382543 \text{ genome 1} \]
\[ \rightarrow 4856482543, 4856, 482543 \rightarrow 4856189264 \rightarrow \text{newgenome1} \]

\[ X_2 = 4.6791, Y_2 = 8.9264 \rightarrow 4679189264 \text{ genome 2} \]
\[ \rightarrow 4679189264, 4679, 189264 \rightarrow 482543 \rightarrow 4679482543 \rightarrow \text{newgenome2} \]

**Same colour build a new Genome with information from both parents (initial values of parameters). The position to cut is random**

**Step 2: Mutation**

\[ \text{newgenome1} \rightarrow \text{mutation} \rightarrow 48561892464 \rightarrow 4856180264 \]
\[ \rightarrow X_1' = 4.8561, Y_1' = 8.9204 \]
\[ \text{newgenome2} \rightarrow \text{mutation} \rightarrow 4679482543 \rightarrow 4679480543 \]
\[ \rightarrow X_2' = 4.6794, Y_2' = 8.2503 \]

**New parameter values:**

\[ X_1 = 4.8563, Y_1 = 8.2543 \rightarrow X_1' = 4.8561, Y_1' = 8.0204 \]
\[ X_2 = 4.6791, Y_2 = 8.9264 \rightarrow X_2' = 4.6794, Y_2' = 8.0503 \]

encoding the parameters as a string-like structure “chromosome”
Methods: Modeling the light curves (cont.)
Pikaia Gracilens, a little worm-like beast that crawled in the mud of a long gone seafloor of the Cambrian era, 530 million years ago. While not particularly impressive in the tooth and claw department, Pikaia is believed to be the founder of the phylum Chordata, whose subsequent evolution had consequences still very much felt today by the rest of the ecosystem. Image digitized from the excellent book The Rise of Fishes, by John A. Long (1995, The Johns Hopkins University Press)

PIKAIA (public domain software High Altitude Observatory, Paul Charbonneau and Barry Knapp V1.2 2002) is a general purpose function optimization FORTRAN-77 subroutine based on a genetic algorithm to solve whatever global optimization problem (Driver program written by Papageorgiou).
Results (KIC 4563150)

EBAL overcontact eclipsing binary system.
$q = 1.77$, $i_0 = 67$, $f(\%) = 51$, $T_{\text{eff}} (\text{K}) = 4998 \pm 143$ (Huber et al. 2014)

Third body candidate (Conroy et al. 2014)

Observations
New ephemeris, same period
PIKAIA + PHOEBE scripter

\(T_1, T_2, [4200K - 6500K], \Omega [4.34 - 4.93], \ i[45 - 80], \ L_3 [0-15\%]\)

Initial population of 120 solutions evolved to 1000 generations
Results (KIC11246163)

Observations
- 471 images
- B (112) V (120) R (120) I (119)
- 8 Minima II
- New ephemeris, same period
- EBAI overcontact eclipsing binary system
- \( q = 1.75 \), \( i^o = 81 \), \( f(\%) = 23 \%
- \( T_{\text{eff}} (K) = 5545 \pm 175 \)

(Huber et al.: 2014)
PIKAIA + PHOEBE scripter

$T_1, T_2, [4500K- 6500K], \Omega [5.86 – 6.48] i [ 70- 100], L_3 [0-15%]$

Initial population of 120 solutions evolved to 1000 generations
<table>
<thead>
<tr>
<th>Parameter</th>
<th>KIC4563150</th>
<th>KIC11246163</th>
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<tbody>
<tr>
<td>$HJD_0$</td>
<td>2456517.48816(20)</td>
<td>2456519.579624(10)</td>
</tr>
<tr>
<td>Period (days)</td>
<td>0.274729(1)</td>
<td>0.279228(1)</td>
</tr>
<tr>
<td>$i^\circ$</td>
<td>62.5(1.0)</td>
<td>89(1.4)</td>
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<tr>
<td>$q=M_2/M_1$</td>
<td>1.77</td>
<td>2.9(1)</td>
</tr>
<tr>
<td>$T_2/T_1$</td>
<td>0.97(1.5)</td>
<td>0.94(2)</td>
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<tr>
<td>$R_2/R_1$</td>
<td>1.29(1)</td>
<td>1.59(1)</td>
</tr>
<tr>
<td>$\Omega_1=\Omega_2$</td>
<td>4.84(5)</td>
<td>6.31(5)</td>
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<tr>
<td>$L_{1B}/L_{B_{tot}}$</td>
<td>0.429(4)</td>
<td>0.336(4)</td>
</tr>
<tr>
<td>$L_{1V}/L_{V_{tot}}$</td>
<td>0.415(3)</td>
<td>0.319(4)</td>
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<tr>
<td>$L_{1Rc}/L_{Rc_{tot}}$</td>
<td>0.407(3)</td>
<td>0.305(4)</td>
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<tr>
<td>$L_{1Ic}/L_{Ic_{tot}}$</td>
<td>0.400(2)</td>
<td>0.300(4)</td>
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<tr>
<td>$L_{2B}/L_{B_{tot}}$</td>
<td>0.571(4)</td>
<td>0.594(6)</td>
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<tr>
<td>$L_{2V}/L_{V_{tot}}$</td>
<td>0.585(3)</td>
<td>0.601(6)</td>
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<td>$L_{2Rc}/L_{Rc_{tot}}$</td>
<td>0.593(3)</td>
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<td>$L_{3B}/L_{B_{tot}}$</td>
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<td>0.070(8)</td>
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<td>$L_{3Ic}/L_{Ic_{tot}}$</td>
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Conroy et al : 2014
### Preliminary Physical Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
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</thead>
<tbody>
<tr>
<td>(T_h) (K)</td>
<td>5092(143)</td>
<td>5786(138)</td>
</tr>
<tr>
<td>(T_2) (K)</td>
<td>4939(143)</td>
<td>5439(138)</td>
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<tr>
<td>(R_h) (R(_\odot))</td>
<td>0.63(0.09)</td>
<td>0.56(0.04)</td>
</tr>
<tr>
<td>(R_c) (R(_\odot))</td>
<td>0.82(0.09)</td>
<td>0.89(0.04)</td>
</tr>
<tr>
<td>(M_h) (R(_\odot))</td>
<td>0.42(0.10)</td>
<td>0.30(0.10)</td>
</tr>
<tr>
<td>(M_c) (R(_\odot))</td>
<td>0.76(0.10)</td>
<td>0.87(0.10)</td>
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</table>

W subtype W UMa
Check the evolutionary status, producing the $\text{LogM-LogL}$, $\text{LogM-LogR}$, with ZAMS and TAMS from BSE code (Hurley et al. 2002)
Period variation

1) extraction of 8000-10000 minima
2) 3000 best TOM
The code *Timing Residuals*, implemented in Python, is set up to handle Heuristic Scanning with parameter perturbation, Bootstrap Resampling, Markov Chain Monte Carlo and the classical approaches of Nelder-Mead and Levenberg-Marquardt algorithms (Papageorgiou & Christopoulou, in preparation).
MCMC sampling method
MCMC (pymc)
Future Work

- Spectroscopic observations $q$, $\text{asini}$, $V$, $3^d$ body
- Fitting using PHOEBE 2.0 (pymc, emcee, lmfit routines etc.)
- PIKAIA +LITE
For simple binaries (or trustable science) – consider using PHOEBE 1 for now.
Thank you for your attention
# Arístarchos Spectrographs

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Wavelength range (Å)</th>
<th>Dispersion</th>
<th>Slit Length</th>
<th>Detector</th>
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<tr>
<td>ATS</td>
<td>4009-7257</td>
<td>-</td>
<td>Fiber: 10&quot; on sky</td>
<td>Alta U47 1kx1k</td>
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<tr>
<td>MES-AT</td>
<td>3900-7500</td>
<td>-</td>
<td>5.8'</td>
<td>2kx2k</td>
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<table>
<thead>
<tr>
<th>gratings</th>
<th>option 1 (RED)</th>
<th>option 2 (BLUE)</th>
<th>option 3</th>
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<td>(grooves/mm)</td>
<td>1200</td>
<td>1200</td>
<td>600</td>
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<tr>
<td>(arcsec)</td>
<td>$\equiv 10$</td>
<td>$\equiv 10$</td>
<td>$\equiv 10$</td>
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<tr>
<td>spectral range</td>
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<td>4309.8-5768.8 Å</td>
<td>4009.0-7257.0 Å</td>
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<tr>
<td>resolution</td>
<td>1.3 Å</td>
<td>1.4 Å</td>
<td>3.2 Å</td>
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<tr>
<td>dispersion</td>
<td>103 Å mm$^{-1}$</td>
<td>95 Å mm$^{-1}$</td>
<td>245 Å mm$^{-1}$</td>
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<td>centered wavelength</td>
<td>6441.6 Å</td>
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<td>5691.5 Å</td>
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