BINARIES: LABORATORIES FOR STELLAR PHYSICS

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Binary stars: laboratories for stellar physics

- Review of binary stars
  1. astrometric binaries
  2. spectroscopic binaries
  3. eclipsing binaries
  4. pulsations in binaries
  5. scientific exploitation
  6. the DEBCat catalogue

- New results for eclipsing binaries
  7. Algol in BRITE light
  8. WASP J0341: the K2 view
  9. AI Phe: the TESS success
Astrometric binaries

- William Herschel (1802) christened the term "binary star"
- Félix Savary (in 1827) established the equations of an astrometric orbit
- What we get from an astrometric binary:
  - period $P$
  - eccentricity $e$
  - inclination $i$
  - semimajor axis $a$ (in arcsec)
- And if we know the distance:
  - semimajor axis $a$ (in au)
  - sum of masses $M_1 + M_2$
Spectroscopic binaries

Vogel (1890) observed the motion of spectral lines in $\beta$ Per
Lehmann-Filhés (1894) established the equations of a spectroscopic orbit
What we get from a spectroscopic binary:

- period $P$, eccentricity $e$
- lower limit on semimajor axis: $a \sin i$
- lower limits on the masses: $M_1 \sin^3 i$ and $M_2 \sin^3 i$
Eclipsing binaries

- John Goodricke (1783) suggested that $\beta$ Persei underwent eclipses.
- Stebbins (1911): measured mass and radius of $\beta$ Aurigae.
- What we get from an EB:
  - period $P$, eccentricity $e$
  - fractional radii of the stars:
    \[ r_1 = \frac{R_1}{a} \quad r_2 = \frac{R_2}{a} \]
  - orbital inclination $i$
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  - period $P$, eccentricity $e$
  - fractional radii of the stars:
    $$ r_1 = \frac{R_1}{a}, \quad r_2 = \frac{R_2}{a} $$
  - orbital inclination $i$
- Eclipses + spectroscopic orbit:
  - masses $M_1$ and $M_2$
  - radii $R_1$ and $R_2$
- Also get $T_{\text{eff}}$ and metallicity from spectroscopy
Pulsations in eclipsing binaries

Kepler light curve of KIC 10661783
(Southworth et al., 2011)
Pulsations in eclipsing binaries

Kepler light curve of KIC 10661783
(Southworth et al., 2011)

Kepler light curve of KIC 11285625
(Debosscher et al., 2013)
Pulsations in eclipsing binaries

Kepler light curve of KIC 10661783
(Southworth et al., 2011)

Kepler light curve of KIC 11285625
(Debosscher et al., 2013)

Kepler light curve of V380 Cyg
(Tkachenko et al., 2014)
Pulsations in eclipsing binaries

Light and velocity curves of KIC 9540226 (Themeßl et al., 2018)
Eclipsing binaries as calibrators of convective core overshooting

- Fit theoretical models to binary star mass, radius, $T_{\text{eff}}$
  - assume same age and chemical composition for the two stars

- Constrain value of core overshooting parameter
  - Claret & Torres (2017, 2018, 2019): fitted for $f_{\text{ov}}$ using MESA and found ramp-up from 1.2 to 2.0 $M_{\odot}$
  - Constantino & Baraffe (2018): unable to reproduce this result
  - Valle et al. (2017): found $f_{\text{ov}} = 0.013 \pm 0.001$ for TZ For
  - Valle et al. (2016): warn of systematic biases unless masses well known
DEBCat: catalogue of well-studied eclipsing binaries

http://www.astro.keele.ac.uk/jkt/debcat/

<table>
<thead>
<tr>
<th>System</th>
<th>Period (days)</th>
<th>$V$ B-V</th>
<th>Spectral type</th>
<th>Mass (M$_\odot$)</th>
<th>Radius (R$_\odot$)</th>
<th>Surface gravity (cgs)</th>
<th>log Teff (K)</th>
<th>log (L/L$_\odot$)</th>
<th>[M/H] (dex)</th>
<th>References and notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>V3903 Sgr</td>
<td>1.744</td>
<td>7.27/0.06</td>
<td>O7.5-V</td>
<td>27.27 ± 0.55</td>
<td>8.088 ± 0.086</td>
<td>4.058 ± 0.016</td>
<td>4.580 ± 0.021</td>
<td>5.087 ± 0.029</td>
<td>4.658 ± 0.032</td>
<td>Vaz et al. (1997&amp;A&amp;A...327.1094V)</td>
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<tr>
<td>V467 Vel</td>
<td>2.753</td>
<td>10.90/0.00</td>
<td>O6.V/o6.V</td>
<td>25.3 ± 0.7</td>
<td>9.99 ± 0.09</td>
<td>3.842 ± 0.016</td>
<td>4.559 ± 0.031</td>
<td>5.187 ± 0.126</td>
<td>3.649 ± 0.110</td>
<td>Michalska et al. (2013MNRAS.429.1354M)</td>
</tr>
<tr>
<td>EM Car</td>
<td>3.414</td>
<td>8.30/-0.31</td>
<td>O8.5-V</td>
<td>22.09 ± 0.32</td>
<td>9.35 ± 0.17</td>
<td>3.856 ± 0.017</td>
<td>4.531 ± 0.026</td>
<td>5.02 ± 0.10</td>
<td>4.82 ± 0.10</td>
<td>Andersen &amp; Clausen (1989&amp;A&amp;A...213.183A)</td>
</tr>
<tr>
<td>DN Cas</td>
<td>2.311</td>
<td>9.93/-0.53</td>
<td>O6.5-V</td>
<td>19.04 ± 0.07</td>
<td>7.72 ± 0.06</td>
<td>4.000 ± 0.009</td>
<td>4.507 ± 0.014</td>
<td>4.70 ± 0.06</td>
<td>4.27 ± 0.08</td>
<td>Baksy et al. (2016PASA...33...46B)</td>
</tr>
<tr>
<td>Y Cyg</td>
<td>2.996</td>
<td>7.32/-0.09</td>
<td>O9.8-B</td>
<td>17.72 ± 0.35</td>
<td>5.785 ± 0.091</td>
<td>4.161 ± 0.014</td>
<td>4.521 ± 0.003</td>
<td>5.00</td>
<td>4.950 ± 0.011</td>
<td>4.47 ± 0.017</td>
</tr>
<tr>
<td>AH Cep</td>
<td>1.775</td>
<td>6.81/0.30</td>
<td>B0.5-V/B0.5-V</td>
<td>16.14 ± 0.25</td>
<td>6.51 ± 0.10</td>
<td>4.019 ± 0.012</td>
<td>4.478 ± 0.008</td>
<td>4.53 ± 0.03</td>
<td>4.30 ± 0.04</td>
<td>Pavlovski, Southworth &amp; Tamajo (2018MNRAS.481.312)</td>
</tr>
<tr>
<td>V478 Cyg</td>
<td>2.881</td>
<td>8.63/0.29</td>
<td>O9.5-V/09.5-V</td>
<td>15.40 ± 0.38</td>
<td>7.26 ± 0.09</td>
<td>3.904 ± 0.099</td>
<td>4.507 ± 0.007</td>
<td>4.70 ± 0.03</td>
<td>4.67 ± 0.04</td>
<td>Pavlovski, Southworth &amp; Tamajo (2018MNRAS.481.312)</td>
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<tr>
<td>V578 Mon</td>
<td>2.408</td>
<td>8.54/0.17</td>
<td>B1.5-V/early-B</td>
<td>14.54 ± 0.08</td>
<td>6.41 ± 0.04</td>
<td>3.931 ± 0.038</td>
<td>4.477 ± 0.007</td>
<td>4.33 ± 0.03</td>
<td>3.86 ± 0.03</td>
<td>Pavlovski, Southworth &amp; Tamajo (2018MNRAS.481.312)</td>
</tr>
<tr>
<td>V453 Cyg</td>
<td>3.890</td>
<td>8.29/0.18</td>
<td>B0.4-V/B0.7-V</td>
<td>13.90 ± 0.23</td>
<td>8.62 ± 0.09</td>
<td>3.710 ± 0.009</td>
<td>4.459 ± 0.008</td>
<td>4.66 ± 0.04</td>
<td>4.42 ± 0.05</td>
<td>Pavlovski, Southworth &amp; Tamajo (2018MNRAS.481.312)</td>
</tr>
<tr>
<td>CW Cep</td>
<td>2.729</td>
<td>7.59/0.28</td>
<td>B0.5-V/B0.5-V</td>
<td>13.52 ± 0.39</td>
<td>5.685 ± 0.130</td>
<td>4.059 ± 0.024</td>
<td>4.452 ± 0.016</td>
<td>4.27 ± 0.06</td>
<td>4.15 ± 0.07</td>
<td>Clausen &amp; Girbez (1991&amp;A&amp;A...241.1980C) &amp; Andersen (1991&amp;A&amp;A...241.1980C)</td>
</tr>
<tr>
<td>V380 Cyg</td>
<td>12.426</td>
<td>5.68/-0.06</td>
<td>B1.5-III</td>
<td>11.43 ± 0.19</td>
<td>15.71 ± 0.13</td>
<td>3.104 ± 0.006</td>
<td>4.336 ± 0.006</td>
<td>4.691 ± 0.041</td>
<td>3.662 ± 0.038</td>
<td>Tiachenko et al. (2014MNRAS.438.3093T)</td>
</tr>
<tr>
<td>DW Car</td>
<td>1.328</td>
<td>9.68/0.07</td>
<td>B1.5-V</td>
<td>11.34 ± 0.12</td>
<td>4.558 ± 0.045</td>
<td>4.175 ± 0.008</td>
<td>4.423 ± 0.016</td>
<td>4.055 ± 0.033</td>
<td>3.915 ± 0.067</td>
<td>Tiachenko et al. (2012MNRAS.424L.21T)</td>
</tr>
<tr>
<td>QX Car</td>
<td>4.478</td>
<td>6.64/-0.23</td>
<td>B2-V/B2-V</td>
<td>9.76 ± 0.12</td>
<td>4.289 ± 0.091</td>
<td>4.140 ± 0.020</td>
<td>4.377 ± 0.009</td>
<td>3.72 ± 0.04</td>
<td>3.58 ± 0.04</td>
<td>Andersen et al. (1983&amp;A&amp;A...121.271A)</td>
</tr>
</tbody>
</table>
$\beta$ Persei as seen by BRITE

- First known eclipsing binary (Goodricke 1783)
- First known spectroscopic binary (Vogel 1890)
- Known to the ancient Egyptians (Jetsu & Porceddu 2015)
- $V = 2.12$: very difficult to get a light curve

Light curve of $\beta$ Per from Stebbins (1910)
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- Observed using two BRITE satellites
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[Preliminary fit to light curve of β Per]
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- \( V = 2.12 \): very difficult to get a light curve
- Observed using two BRITE satellites
- Preliminary fit with the Wilson-Devinney code
- Spectroscopic orbit based on 1000 ESPaDOnS spectra
  - triple system with faint secondary
  - non-Keplerian effects visible in the RVs
Eclipsing binary near the Pleiades found in the SuperWASP data
- we proposed it for *Kepler K2 Campaign 4*
- solar-type system (5500 K) with weak tidal effects
- orbital period 8.07 d, eccentricity 0.037

Plot shows *EVEREST* systematics-corrected light curve
K2 light curve modelled using JKTEBOP code
- account for eccentricity, limb darkening, cadence
1SWASP J034114.25+201253.5

- K2 light curve modelled using JKTEBOP code
  - account for eccentricity, limb darkening, cadence
- Residuals increase during eclipse
  - indicates weak spot activity on primary star (star eclipsed at phase zero)
- 6.0-d rotation period ⇒ star(s) not rotationally synchronised
23 spectra obtained from TRES échelle spectrograph
- scatter of 0.20 km s$^{-1}$ for primary and 0.32 km s$^{-1}$ for secondary
- systemic velocity rejects membership of Pleiades
1SWASP J034114.25+201253.5

- 6 spectra obtained from VLT/UVES
  - sample six different orbital phases
  - total S/N of 300
- Will be separated using spectral disentangling
  - obtain $T_{\text{eff}}$ and chemical composition of each component
  - provide detailed constraints on theoretical models
SWASP J034114.25+201253.5

- Masses and radii measured to high precision:
  - $M_1 = 1.079 \pm 0.003 \, M_\odot$
  - $M_2 = 0.948 \pm 0.002 \, M_\odot$
  - $R_1 = 1.213 \pm 0.003 \, R_\odot$
  - $R_2 = 0.933 \pm 0.007 \, R_\odot$
  - These are not the final numbers

- Preliminary: $T_{\text{eff}} = 6000 \pm 200 \, \text{K}$
  - mass–radius diagram good match to models
  - mass–$T_{\text{eff}}$ disagrees
  - YY models for age 5.4 Gyr
  - DSEP models for age 5.2 Gyr
AI Phoenicis: subgiant eclipsing binary

- Often-studied eclipsing binary (Strohmeier 1972)
  - MS star: 1.20 \( M_\odot \), 1.84 \( R_\odot \)
  - subgiant: 1.25 \( M_\odot \), 2.91 \( R_\odot \)

- Hełminiak et al. (2009) measured the masses to 0.36% precision

- How well can we measure the radii?

SuperWASP photometry
Hare-and-hounds exercise to see if different people get the same results

1. work independently
2. use the TESS light curve
3. orbital period 24.5924 d
4. determine $r_1$, $r_2$, $i$, $e$ and $\omega$
AI Phoenicis: TESS light curve

- Hare-and-hounds exercise to see if different people get the same results
  1. work independently
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  3. orbital period 24.5924 d
  4. determine $r_1$, $r_2$, $i$, $e$ and $\omega$
AI Phoenicis: do we agree?

- Results: radii to 0.1–0.2%
  - agree to 0.27% on radius of primary (MS star)
  - agree to 0.05% on radius of secondary (subgiant)

- Work in progress to check and standardise the analyses
Next stop: PLATO

PLATO WP 161: Binary and Multiple Stars