BINARY STARS: ECLIPSES, PULSATIONS, FUTURE

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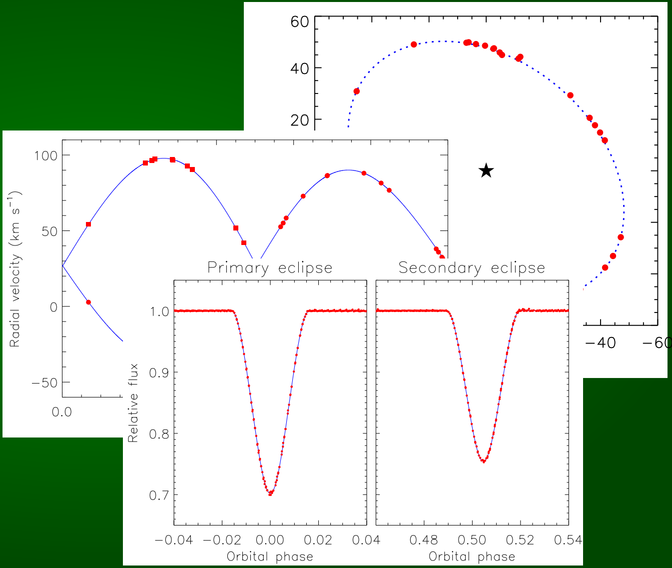
Binary stars: laboratories for stellar physics

- Review of binary stars
  - astrometric binaries
  - spectroscopic binaries
  - eclipsing binaries
  - the DEBCat catalogue
  - impact of *Gaia*
- Pulsations in eclipsing binaries
  - history
  - new results from TESS
  - the SWIPE project
  - Worked example: KIC 9851944
- The future: PLATO



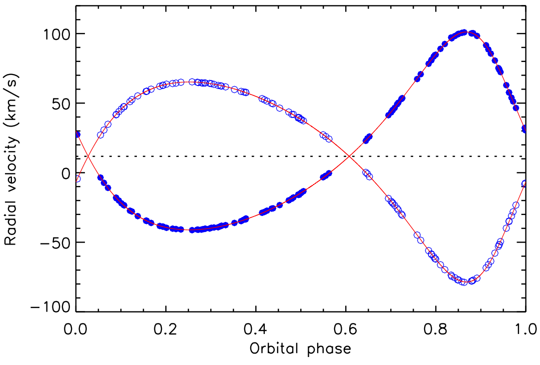
Astrometric binaries

- 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)
- If we know the distance:
  - semimajor axis a (in au)
  - sum of masses $M_1 + M_2$

Albireo (Richard Yandrik)

Spectroscopic binaries

- Vogel (1890) observed the motion of spectral lines in β Persei
- Rambaut (1891) measured the first spectroscopic orbit, of β Aurigae
- 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 $M_2 \sin^3 i$



V1022 Cas (data from Lester et al., 2019)

Eclipsing binaries

- John Goodricke (1783) suggested that β Persei underwent eclipses
- Stebbins (1911): measured mass and radius of β Aurigae
- What we get from an EB:
  - period P, eccentricity e
  - fractional radii: $r_{1,2} = \dfrac{R_{1,2}}{a}$
  - orbital inclination i

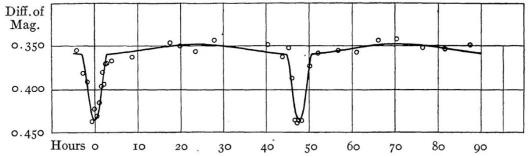
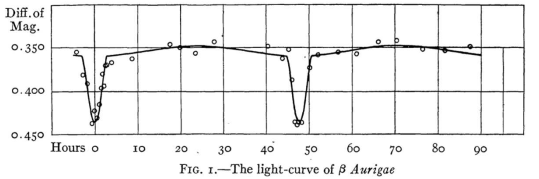


FIG. 1.—The light-curve of β *Aurigae*

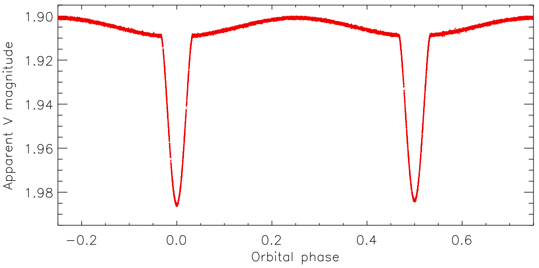
Light curve of β Aurigae (Stebbins 1911)

Eclipsing binaries

- John Goodricke (1783) suggested that β Persei underwent eclipses
- Stebbins (1911): measured mass and radius of β Aurigae
- What we get from an EB:
  - period P, eccentricity e
  - fractional radii: $r_{1,2} = \frac{R_{1,2}}{a}$
  - orbital inclination i
- Eclipses + spectroscopic orbit:
  - masses M_1 and M_2
  - radii R_1 and R_2
- Get $T_{\rm eff}$ and metallicity from spectroscopy



Light curve of β Aurigae (Stebbins 1911)

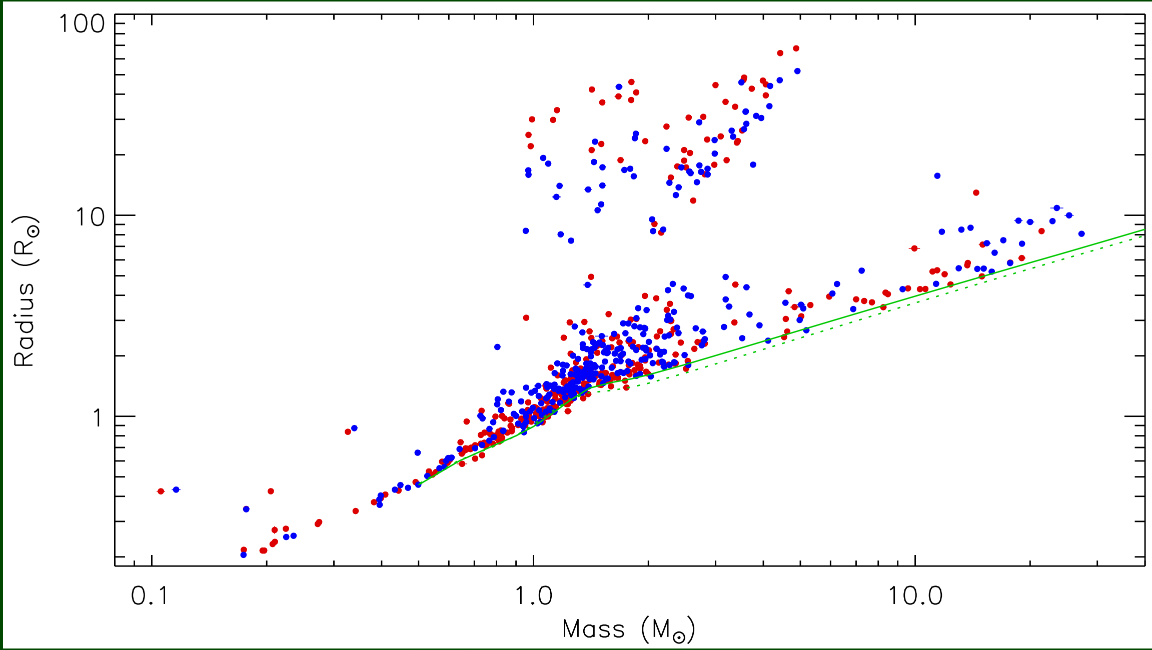


Light curve of β Aurigae (Southworth et al., 2007)

DEBCat: catalogue of well-studied eclipsing binaries

System	Period (days)	V B-V	Spectral type	Mass (Msun)	Radius (Rsun)	Surface gravity (cgs)	log Teff (K)	log (L/Lsun)	[M/H] (dex)	References and notes
V3903 Sgr	1.744	7.27 0.06	O7_V O9_V	27.27 ± 0.55 19.01 ± 0.44	8.088 ± 0.086 6.125 ± 0.060	4.058 ± 0.016 4.143 ± 0.013	4.580 ± 0.021 4.531 ± 0.021	5.087 ± 0.029 4.658 ± 0.032		Vaz et al. (1997A&A...327.1094V)
V467 Vel	2.753	10.90 0.00	O6_Vf B1_V	25.3 ± 0.7 8.25 ± 0.17	9.99 ± 0.09 3.49 ± 0.03	3.842 ± 0.016 4.268 ± 0.017	4.559 ± 0.031 4.402 ± 0.046	5.187 ± 0.126 3.649 ± 0.110		Michalska et al. (2013MNRAS.429.1354M)
CC Cas	3.366	7.08 0.48	O8.5_III B0.5_V	23.49 ± 0.92 9.95 ± 0.34	10.87 ± 0.18 6.84 ± 0.18	3.736 ± 0.013 3.766 ± 0.022	4.538 ± 0.025 4.452 ± 0.031	5.179 ± 0.053 4.474 ± 0.064		Southworth & Bowman (2022MNRAS.513.3191S)
EM Car	3.414	8.38 -0.31	O8_V O8_V	22.89 ± 0.32 21.43 ± 0.33	9.35 ± 0.17 8.34 ± 0.14	3.856 ± 0.017 3.926 ± 0.016	4.531 ± 0.026 4.531 ± 0.026	5.02 ± 0.10 4.92 ± 0.10		Andersen & Clausen (1989A&A...213..183A)
δ Cir	3.902	5.09 -0.06	O7_IV O9.5_V	20.00 ± 0.50 11.41 ± 0.24	9.256 ± 0.091 5.326 ± 0.091	3.806 ± 0.007 4.043 ± 0.014	4.574 ± 0.010 4.519 ± 0.013	5.184 ± 0.070 4.339 ± 0.090		Southworth & Bowman (2022MNRAS.513.3191S)
DN Cas	2.311	9.93 0.53	O8_V B0.2_V	19.04 ± 0.07 13.73 ± 0.05	7.22 ± 0.06 5.79 ± 0.06	4.000 ± 0.009 4.270 ± 0.010	4.507 ± 0.014 4.447 ± 0.017	4.70 ± 0.06 4.27 ± 0.08		Bakış et al. (2016PASA...33...46B)
V1292 Sco	4.240	7.57 0.14	O9.5_III B1-2_IV	18.64 ± 0.47 7.70 ± 0.12	9.40 ± 0.15 3.69 ± 0.06	3.762 ± 0.018 4.190 ± 0.016	4.490 ± 0.014 4.336 ± 0.020			Rosu et al. (2022A&A...664A..98R)
Y Cyg	2.996	7.32 -0.09	O9.8_V O9.8_V	17.72 ± 0.35 17.73 ± 0.30	5.785 ± 0.091 5.816 ± 0.063	4.161 ± 0.014 4.157 ± 0.010	4.521 ± 0.003 4.525 ± 0.003		0.00 ± 0.00	Harmanec et al. (2014A&A...563A.120H)
V1034 Sco	2.441	8.47 -0.22	O9.5_V B1_V	17.01 ± 0.14 9.573 ± 0.053	7.513 ± 0.075 4.328 ± 0.051	3.917 ± 0.009 4.147 ± 0.010	4.508 ± 0.007 4.412 ± 0.005	4.738 ± 0.028 3.874 ± 0.028	0.00 ± 0.00	Pavlovski et al. (2023A&A...671A.139K) Rosu et al. (2022A&A...664A..98R)
AH Cep	1.775	6.81 0.30	B0.5_V B0.5_V	16.14 ± 0.26 13.69 ± 0.21	6.51 ± 0.10 5.64 ± 0.11	4.019 ± 0.012 4.073 ± 0.018	4.487 ± 0.008 4.459 ± 0.008	4.53 ± 0.03 4.30 ± 0.04	0.00 ± 0.00	Pavlovski, Southworth & Tamajo (2018MNRAS.481.3129P) Holmgren et al. (1990A&A...236..409H)
GL Car	2.422	9.70 0.17	B0.5_V B1_V	15.86 ± 0.31 14.95 ± 0.30	5.242 ± 0.048 4.968 ± 0.051	4.199 ± 0.007 4.220 ± 0.008	4.491 ± 0.007 4.483 ± 0.007	4.357 ± 0.029 4.278 ± 0.030	0.00 ± 0.00	Pavlovski et al. (2023A&A...671A.139K) Gimenez & Clausen (1986A&A...161..275G)
V478 Cyg	2.881	8.63 -0.29	O9.5_V O9.5_V	15.40 ± 0.38 15.02 ± 0.35	7.26 ± 0.09 7.15 ± 0.09	3.904 ± 0.009 3.907 ± 0.010	4.507 ± 0.007 4.502 ± 0.008	4.70 ± 0.03 4.67 ± 0.04	0.00 ± 0.00	Pavlovski, Southworth & Tamajo (2018MNRAS.481.3129P) Popper & Hill (1991AJ....101..600P)
V573 Car	1.469	9.52 0.11	O9.5_V B0.3_IV	15.11 ± 0.13 12.37 ± 0.10	5.429 ± 0.043 4.528 ± 0.049	4.148 ± 0.007 4.218 ± 0.009	4.504 ± 0.005 4.458 ± 0.005	4.439 ± 0.023 4.098 ± 0.023	0.00 ± 0.00	Pavlovski et al. (2023A&A...671A.139K) Freyhammer et al. (2001AA&A...369..561F)
V578 Mon	2.408	8.54 0.17	B1_V: early_B	14.54 ± 0.08 10.29 ± 0.06	5.41 ± 0.04 4.29 ± 0.05	4.133 ± 0.018 4.185 ± 0.021	4.477 ± 0.007 4.411 ± 0.007	4.33 ± 0.03 3.86 ± 0.03	0.00 ± 0.00	Garcia et al. (2014AJ....148...39G) Pavlovski, Southworth & Tamajo (2018MNRAS.481.3129P)
V453 Cyg	3.890	8.29 0.18	B0.4_IV B0.7_IV	13.96 ± 0.23 11.10 ± 0.18	8.665 ± 0.055 5.250 ± 0.056	3.708 ± 0.004 4.044 ± 0.009	4.459 ± 0.008 4.442 ± 0.009	4.666 ± 0.031 4.163 ± 0.039	0.00 ± 0.00	Southworth et al. (2020MNRAS.497L..19S) Pavlovski, Southworth & Tamajo (2018MNRAS.481.3129P)
OGLE LMC-ECL-22270	5.414	14.03	none	13.21 ± 0.08	8.48 ± 0.10	3.702 ± 0.010	4.417 ± 0.027	4.478 ± 0.010		Taormina et al. (2020ApJ...890..137T)

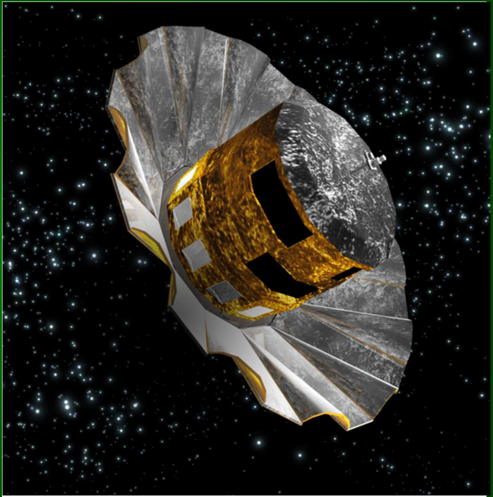
http://www.astro.keele.ac.uk/jkt/debcat/



100
10
1
0.1
1.0
10.0
Radius (R⊙)
Mass (M⊙)

Gaia and binary stars

- *Gaia* epoch photometry useful for cataloguing binary stars
  - Mowlavi et al. (2022) found 2.2 million
  - sparse photometry bad for longer periods



ESA / C. Carreau

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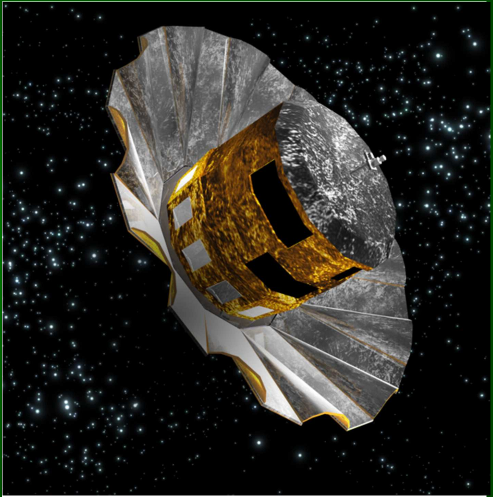
- *Gaia* parallaxes useful for temperature measurement
  - *Gaia* parallax + known radii $\Rightarrow T_{\mathrm{eff}}$



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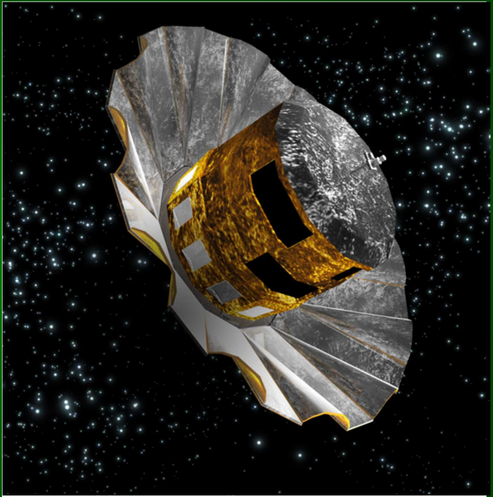
- *Gaia* parallaxes useful for temperature measurement
  - *Gaia* parallax + known radii $\Rightarrow T_{\text{eff}}$
- *Gaia* RVS spectra useful for orbit determination
  - SB1 and SB2 orbits catalogued (TBOSB1 and TBOSB2)
  - reliability not yet demonstrated



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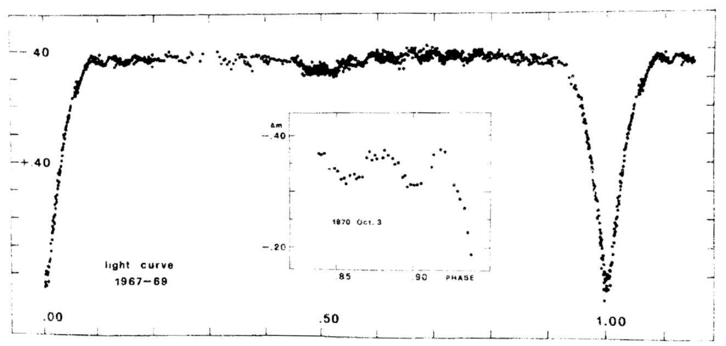
Pulsations in eclipsing binaries

Light curve of AB Cas
(Tempesti, 1971)



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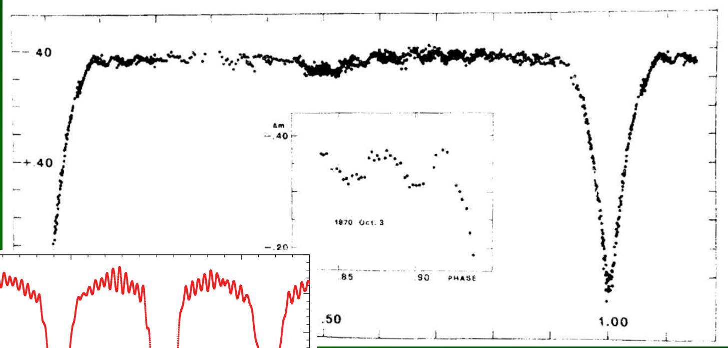
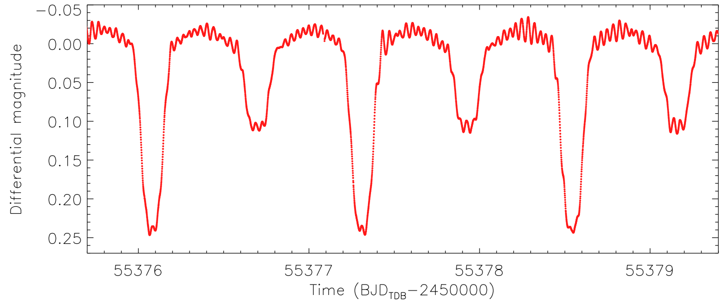
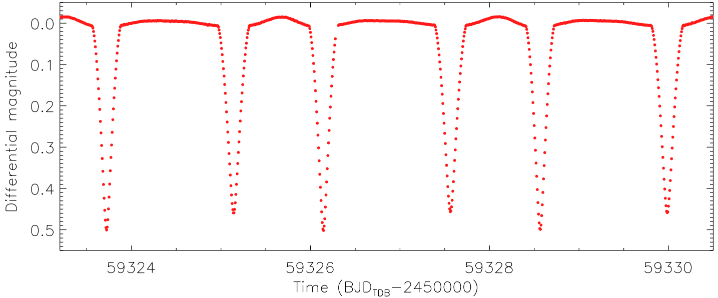




Kepler light curve of
KIC 10661783
(Southworth et al., 2011)

New results from TESS

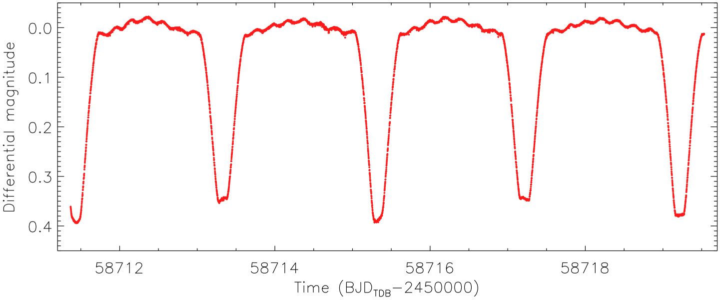
- Well-known eclipsing binaries
  - GL Car ($P = 2.42\,\mathrm{d}$)



TESS light curve of GL Car (Pavlovski et al., 2023)

New results from TESS

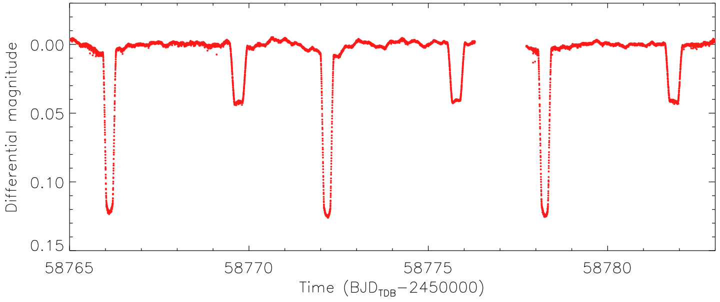
- Well-known eclipsing binaries
  - GL Car ($P = 2.42$ d)
- β Cephei stars in EBs
  - V453 Cyg ($P = 3.89$ d)



TESS light curve of V453 Cyg (Southworth et al., 2020)

New results from TESS

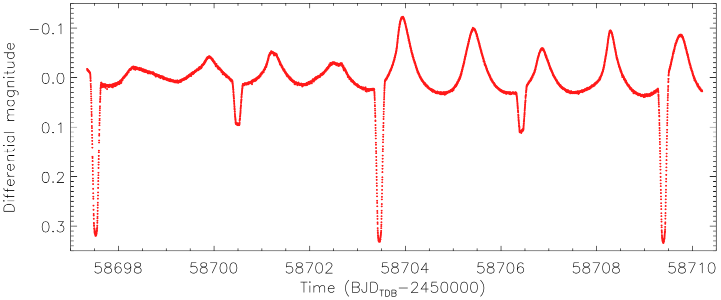
- Well-known eclipsing binaries
  - GL Car ($P = 2.42\,\mathrm{d}$)
- β Cephei stars in EBs
  - V453 Cyg ($P = 3.89\,\mathrm{d}$)
- Slowly-pulsating B-stars in EBs
  - AR Cas ($P = 6.07\,\mathrm{d}$)



TESS light curve of AR Cas (in preparation)

New results from TESS

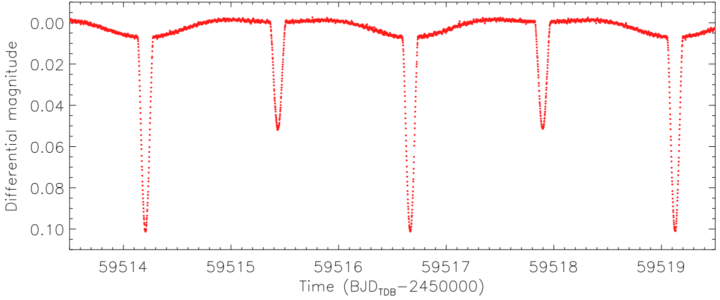
- Well-known eclipsing binaries
  - GL Car ($P = 2.42$ d)
- β Cephei stars in EBs
  - V453 Cyg ($P = 3.89$ d)
- Slowly-pulsating B-stars in EBs
  - AR Cas ($P = 6.07$ d)
- γ Doradus stars in EBs
  - V2077 Cyg ($P = 5.94$ d)



TESS light curve of V2077 Cyg (Southworth & Van Reeth, 2022)

New results from TESS

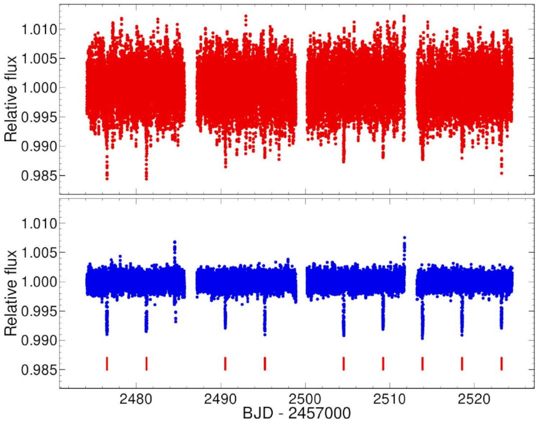
- Well-known eclipsing binaries
  - GL Car ($P = 2.42$ d)
- β Cephei stars in EBs
  - V453 Cyg ($P = 3.89$ d)
- Slowly-pulsating B-stars in EBs
  - AR Cas ($P = 6.07$ d)
- γ Doradus stars in EBs
  - V2077 Cyg ($P = 5.94$ d)
- δ Scuti stars in EBs
  - HD 23642 ($P = 2.46$ d)



TESS light curve of HD 23642 (Southworth et al., 2023)

New results from TESS

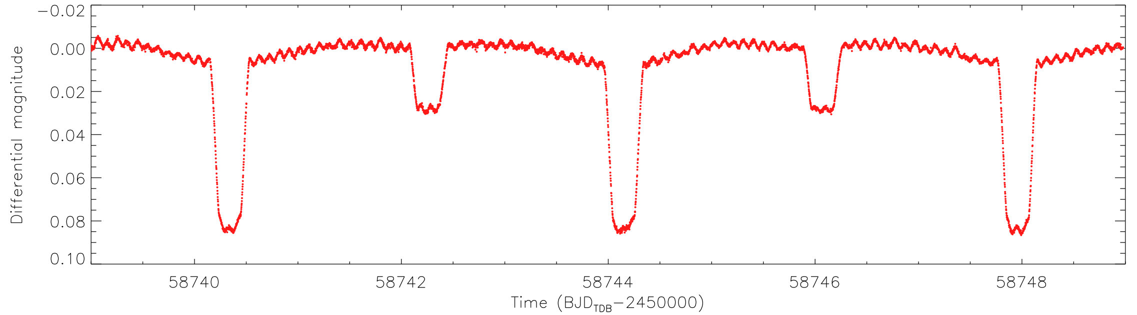
- Well-known eclipsing binaries
  - GL Car ($P = 2.42$ d)
- β Cephei stars in EBs
  - V453 Cyg ($P = 3.89$ d)
- Slowly-pulsating B-stars in EBs
  - AR Cas ($P = 6.07$ d)
- γ Doradus stars in EBs
  - V2077 Cyg ($P = 5.94$ d)
- δ Scuti stars in EBs
  - HD 23642 ($P = 2.46$ d)
- Substellar objects in EBs
  - HD 31221 ($P = 4.67$ d)



TESS light curve of HD 31221 (Kálmán et al., 2023)

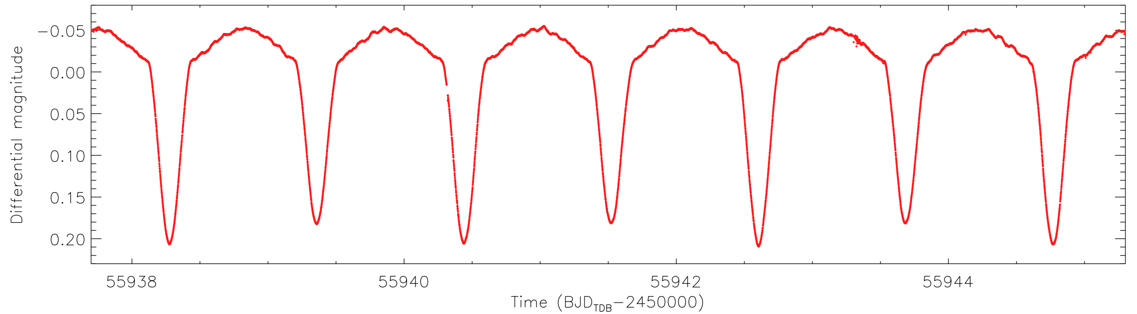
SWIPE: Stars With Pulsations and Eclipses

- Project to study eclipsing binaries also showing pulsations
- 9 collaborators (Keele, Leeuven, Zagreb, Queensland)
- 11 publications so far + 4 in progress



https://www.astro.keele.ac.uk/jkt/swipe/

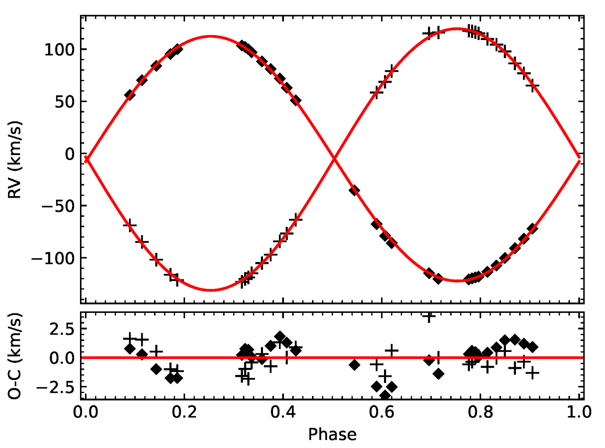
KIC 9851944: a case study



- Identified as an EB with γ Dor period spacings by Li et al. (2020)
- Already known as a nice EB from *Kepler* (Guo et al., 2016)
  - 4 years long cadence, 5 quarter short cadence
- 32 échelle spectra from Lick 3 m

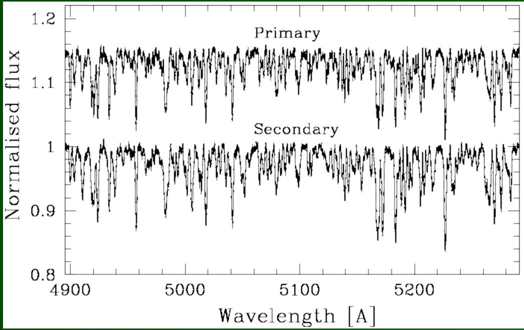
Jennings et al.
(almost submitted)

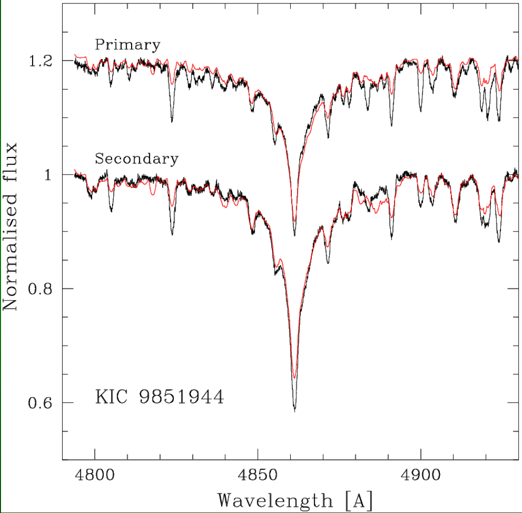
KIC 9851944: spectroscopic orbit



- Cross-correlation with TODCOR
- Masses 1.747 ± 0.010 and 1.867 ± 0.010 $M_\odot$

KIC 9851944: spectral disentangling

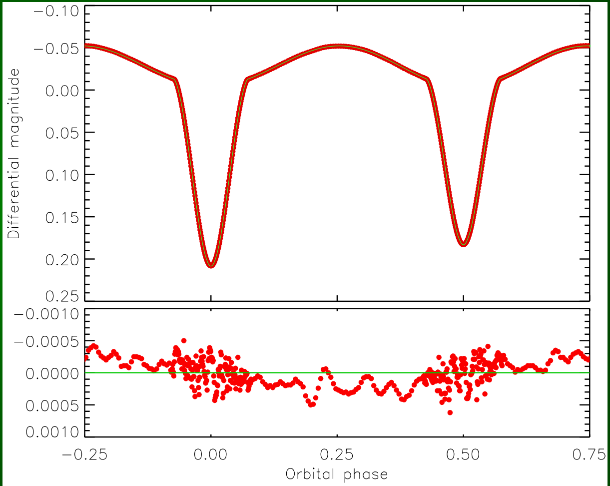




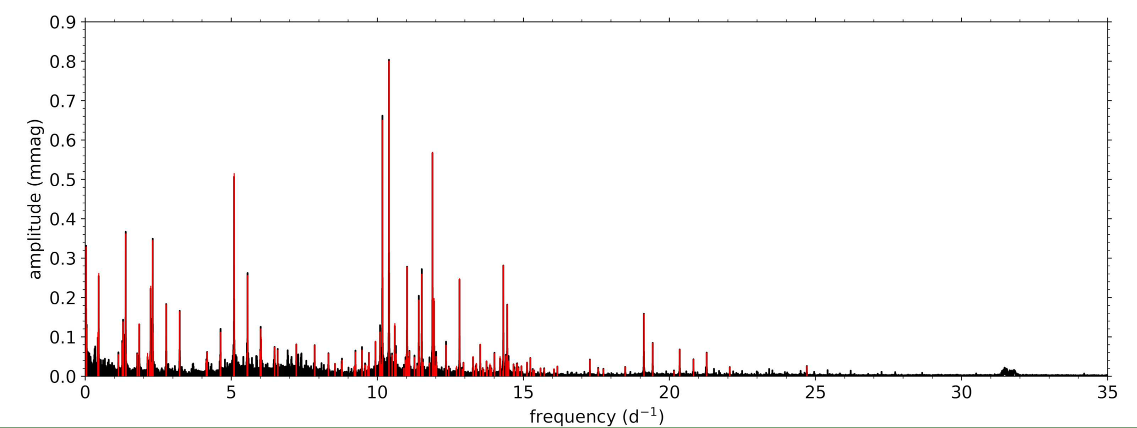
- Get spectra and orbits of the two stars from the set of composite spectra (Simon & Sturm 1994)
- Fit Balmer lines to synthetic spectra
- Temperatures: 6964 ± 43 and 6840 ± 37 K

KIC 9851944: eclipse analysis

- Preliminary fit with JKTEBOP
- Phase-bin into 400 points
- Final fit with Wilson-Devinney code
- Radii: 2.532 ± 0.026 and 2.981 ± 0.044 $R_\odot$

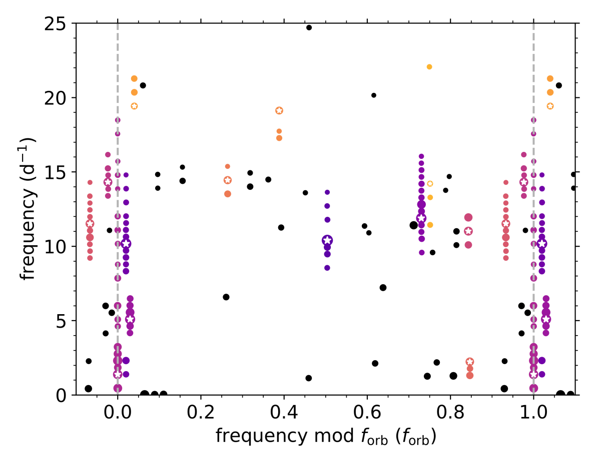


KIC 9851944: pulsation analysis

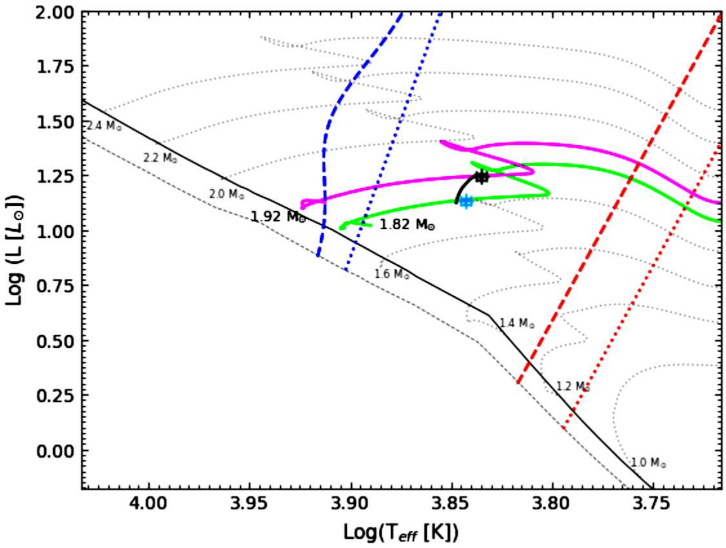


KIC 9851944: pulsation analysis

- 133 significant frequencies
- p-modes (δ Sct) and g-modes (γ Dor)
- Pulsations from both stars
- Tidal perturbation and excitation
- g-mode pulsations:
  - buoyancy radius: $\Pi_0 = 4370^{+690}_{-660}$ s
  - near-core rotation period $0.49^{+0.05}_{-0.06}$ d



KIC 9851944: evolutionary status



PLATO – PLAnetary Transits and Oscillations

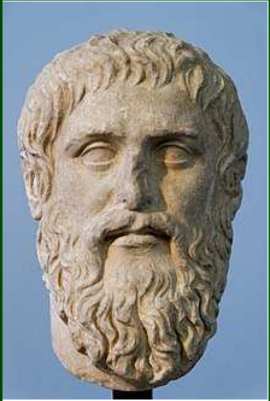


Image credits:
M. Nguyen (Wikipedia)
ESA/ATG Medialab
ESA/L. Calčada

- 26-camera planet search mission
- ESA launch late 2026 (dhyb)
- EBs are part of Complementary Science
  - WP 161 000 Binary and multiple star systems (PI Southworth)
  - WP 125 500 PLATO Benchmark Stars (PIs Creevey & Maxted)
- "Binary Stars with Space Telescopes"
  - Conference at Keele University
  - June/July 2025