Improving fundamental astrophysics with eclipsing binary stars

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Theoretical basis for the method

$$f_{0,b} = f_{0,1} + f_{0,2} = \frac{\sigma_{\rm SB}}{4}\left[\theta_1^2 {\rm T}_{\rm eff,1}^4 + \theta_2^2 {\rm T}_{\rm eff,2}^4\right]$$

Bolometric flux, f_0 for both components

- Need flux ratios in UV, visible and NIR
- Need to consider interstellar reddening
- Additional uncertainty from CALSPEC flux scale: **±1-2%**

Angular diameters, $\theta = 2R\varpi$

- Radius for stars in detached EBs known to **±0.5%** or better
- Parallax from Gaia EDR3 **±20-30 μas**

Bolometric flux for both stars

Use measurements of flux for both stars across optical range:

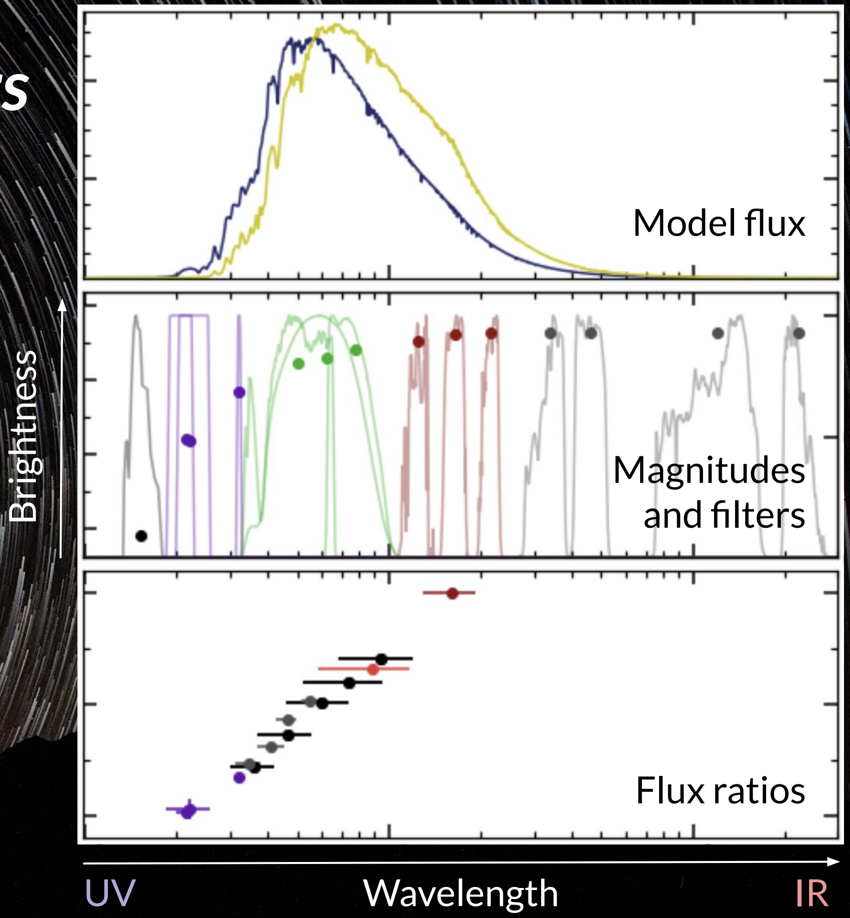
- ★ Flux ratios
- ★ Catalog photometry
- ★ Colors (e.g. Strömgren)

We need model SEDs for small-scale spectral features:

- ★ *BT-Settl & BT-Settl-CIFIST*

E(B-V) estimated via EW fitting of Na DI line

Munari & Zwitter 1997



Distorting the flux distributions

Assume true SED = model SED x distortion:

$$\mathcal{F}_{\lambda,\mathrm{true}} = \mathcal{F}_{\lambda,\mathrm{model}} \times \left[1 + \Sigma c_\ell P_\ell(x)\right]$$

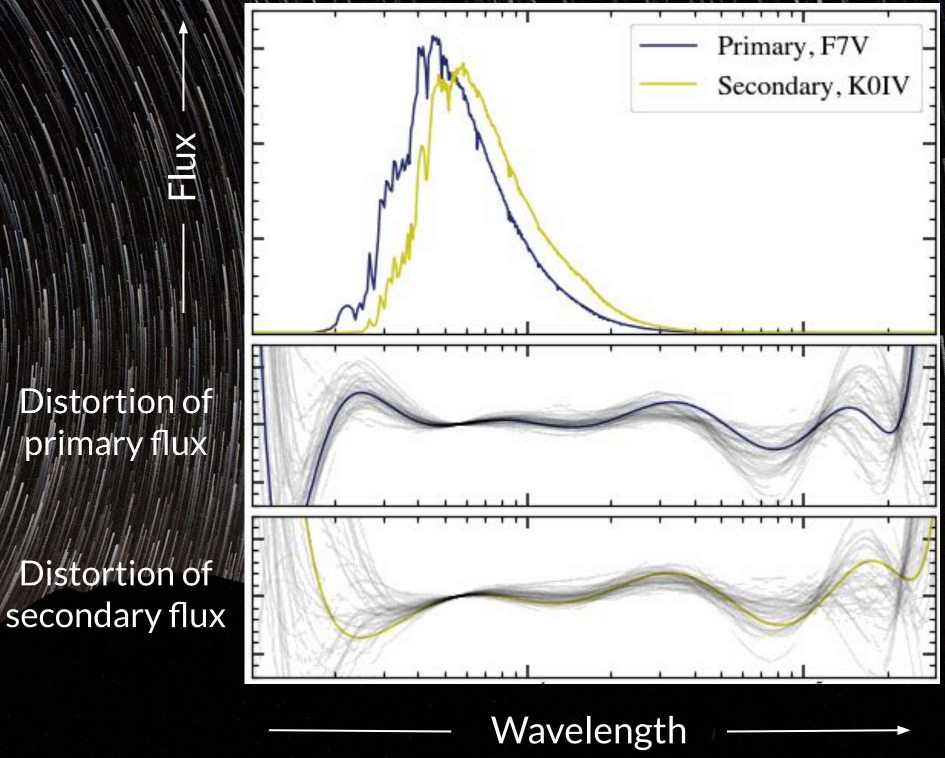
where $P_\ell(x)$ are Legendre polynomials.

These “integrating functions” are normalised, and so

$$f_{\lambda,\oplus} = \sigma_{SB}\, T_{\mathrm{eff},1}^4\, \theta_1^2\, \mathcal{F}_\lambda$$

Distortion and normalisation

⇒ this is not regular SED fitting



Model parameters $\boldsymbol{M}$

- $T_{eff,1}$; $T_{eff,2}$
- θ_1 ; θ_2
- $E(B\text{-}V)$
- Distortion coefficients, $c_{\ell,1}$; $c_{\ell,2}$
- Extra error on magnitudes, σ_{ext}
- " " " flux ratios, σ_L
- " " " colors, σ_C

Data $\boldsymbol{D}$

- $\theta_1 \pm \sigma_{\theta,1}$; $\theta_2 \pm \sigma_{\theta,2}$
- Magnitudes, $m_{X,i} \pm \sigma_{X,i}$
- Flux ratios, $L_{\lambda,i} \pm \sigma_{L,i}$

Meta-data / assumptions $\boldsymbol{A}$

- Response functions, $R_X(\lambda)$
- Zero-points, $ZP_X \pm \sigma_{ZP,X}$
- $\mathcal{F}_{\lambda,model,1}$; $\mathcal{F}_{\lambda,model,2}$

Use `emcee` to sample

$$\mathrm{P}(\boldsymbol{M} \mid \boldsymbol{D}, A) = \mathrm{P}(\boldsymbol{D} \mid \boldsymbol{M}, A)\,\mathrm{P}(\boldsymbol{M})$$

AI Phoenicis: A well-studied F7V + K0IV binary

- Detached, totally eclipsing V~8.6 binary with 24 day orbital period
- Wealth of quality light curves throughout optical range
- Exceptionally accurate radii
  - Maxted et al 2020
- Independent parallax measurement
  - Gallenne et al 2019

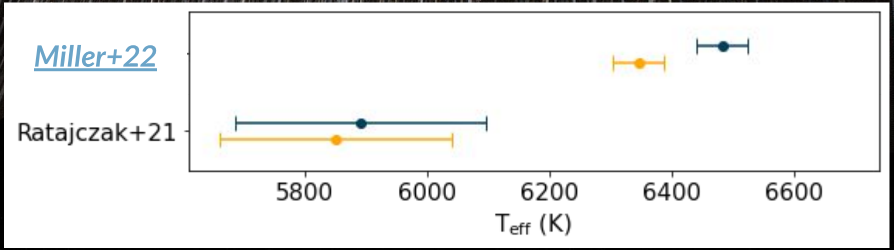
Parameter		***Primary***	***Secondary***
Radius [$R_\odot$]	0.12%	1.8036 ± 0.0022	2.9303 ± 0.0023
Mass [$M_\odot$]	0.06%	1.1938 ± 0.0008	1.2438 ± 0.0008
log g [dex]	0.03%	4.0020 ± 0.0011	3.5981 ± 0.0009
T_{eff} [K]	0.35%	6199 ± 22	5094 ± 16
L [$L_\odot$]	1.45%	4.329 ± 0.0627	5.207 ± 0.065

Our results for AI Phe ⟶ ***Miller et al 2020***

CPD-54 810 : A detached F5V + F6V binary

- a.k.a. ASAS J051753-5406.0
  📎 Ratajczak et al 2021
- Detached V~10.5 binary with 26 day orbital period
- Standard catalog photometry (including *TESS* light curve) + additional BVRI light curves with *PEST*
- More of a challenge than AI Phe
  ⚠️ Similar spectral types
  ⚠️ Fewer data available

Parameter		*Primary*	*Secondary*
Radius [$R_\odot$]	0.2%	1.929 ± 0.003	1.182 ± 0.004
Mass [$M_\odot$]	0.4%	1.309 ± 0.005	1.090 ± 0.003
log *g* [dex]	0.02%	3.984 ± 0.001	4.330 ± 0.003
T_{eff} [K]*	0.7%	6462 ± 43	6331 ± 43



The "Swift" sample and beyond

TYC 7091-888-1 — F6V+K0IV (MS turn-off)

V530 Ori — G1V+M1V

LL Aqr — F9V+G3V (solar twin)

V501 Her — G3IV+G3V

TYC 6511-1799-1 — F9IV+G0IV

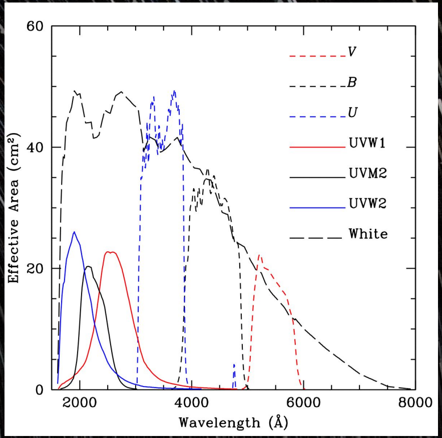
BK Peg — F8V+F7V

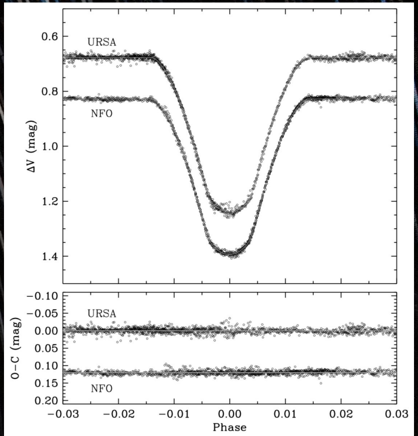
+11 additional EBs

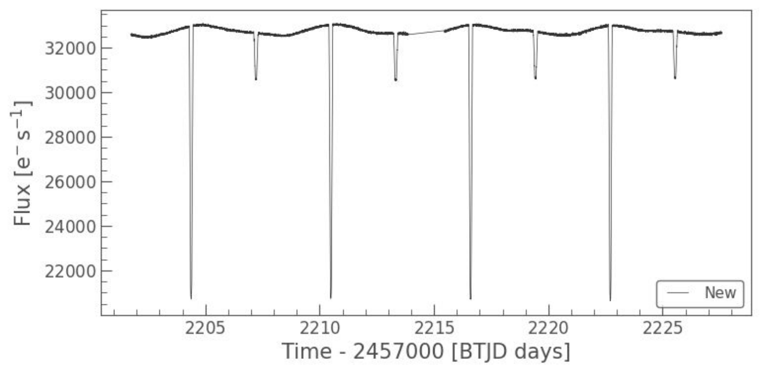
Temperatures for Eclipsing Binary stars

Swift UVOT observations → calibrated AB magnitudes

New TESS light curves + HR spectra → orbits, E(B-V)







Activities in 2023

Ongoing projects and publications

- ***Fundamental Teff for Eclipsing Binary Stars V*** *paper analysing 3 EBs of Swift sample, in prep.*
- ***Fundamental Teff for Eclipsing Binary Stars VI*** *paper with remaining 3 Swift EBs, awaiting OCM data*
- ***Benchmark spectra for benchmark EBs*** *contributor to paper in prep + submitted observing proposals*
- ***Fundamental Teff for SBCR eclipsing binaries*** *in collaboration with Graczyk, Gałan*
- ***E(B-V) calibration using Na DI lines*** *exploratory work using spectroscopy of WDs*

Collaborations and other activities

- ***Co-I of 2 successful ESO proposals*** *to observe RVs of benchmark stars*
- ***Co-author on 2 papers*** *using CHEOPS to study eclipsing binary stars*
- ***Contributor*** *to Araucaria Project, OCM and PLATO "Benchmark stars" work package*
- ***Seminar talk*** *and visitor at CAMK Toruń*
- ***Visitor*** *at University of Warwick and Keele University*
- ***Outreach activities*** *at International Astronomical Youth Camp; President of IWA e.V and volunteer*

International Astronomical Youth Camp

Duration *— 3 weeks in July/August*

Age range *— 16 – 24*

Location *— Germany (2023, 2024)*

 # Participants *— 65*

 # Nationalities *— 25 – 30*

Activities *— Original research in small groups, practical astronomy, cultural exchange*

Topics *— Astrophysics, cosmology, theoretical, engineering, astrobiology, instrumentation, …*

Fee *— 1090€ (2024)*