Single and Double Cepheids in Binary Systems

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Richard Anderson

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Nancy Evans

Alexandre Gallenne

Pierre Kervella

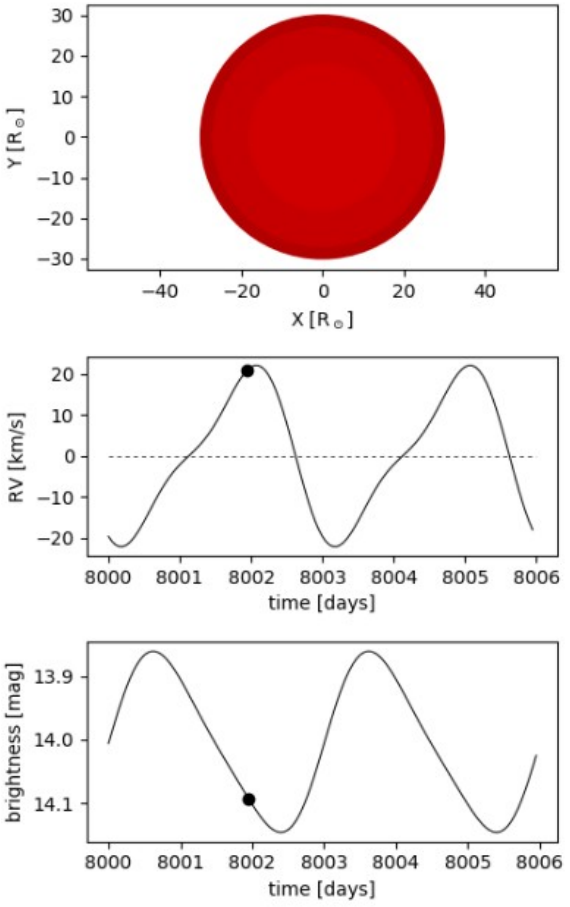
Ian Thompson

...

Introduction

Pulsating stars
radial pulsations

- **Radially pulsating stars**
  - cyclic radius change
  - temperature change
  - => brightness change
- **Crossing the *instability strip***
  - internal conditions make star unstable against pulsations
  - period depends on physical parameters
- **Examples:**
  - classical Cepheids
  - type II Cepheids



Short history of Cepheids

- **First observed in 1784**
  - XIX century: regular observations
- **Beginning of XX century**
  - period – luminosity relation *(Leavitt 1912)*
  - good distance indicators
- **Towards Hubble constant...**
  - spiral nebulae are distant galaxies
  - distant galaxies are red-shifted
  - Hubble diagram (velocity vs. distance)
  - first measurement of H_0 (500 km/s/Mpc)
- **Base for H_0 measurement in XXI c.**
  - 1.4% precision, 73 km/s/Mpc (Riess+2022)

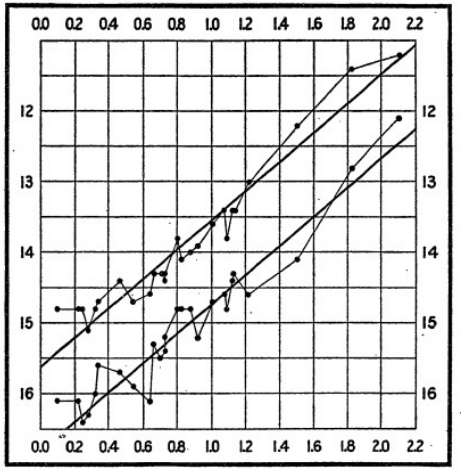


FIG. 2.

A RELATION BETWEEN DISTANCE AND RADIAL VELOCITY AMONG EXTRA-GALACTIC NEBULAE

BY EDWIN HUBBLE

MOUNT WILSON OBSERVATORY, CARNEGIE INSTITUTION OF WASHINGTON

Communicated January 17, 1929

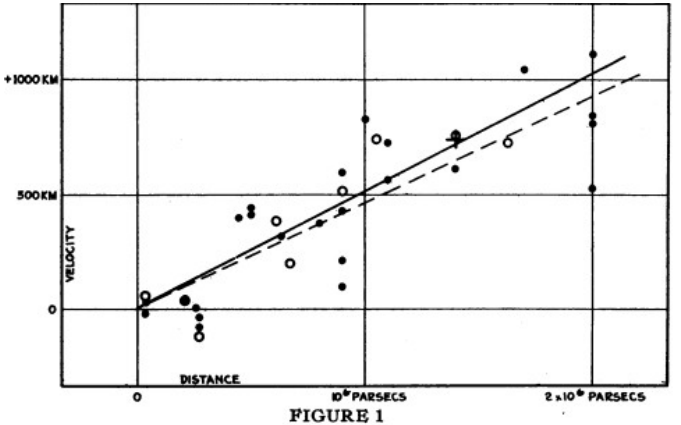
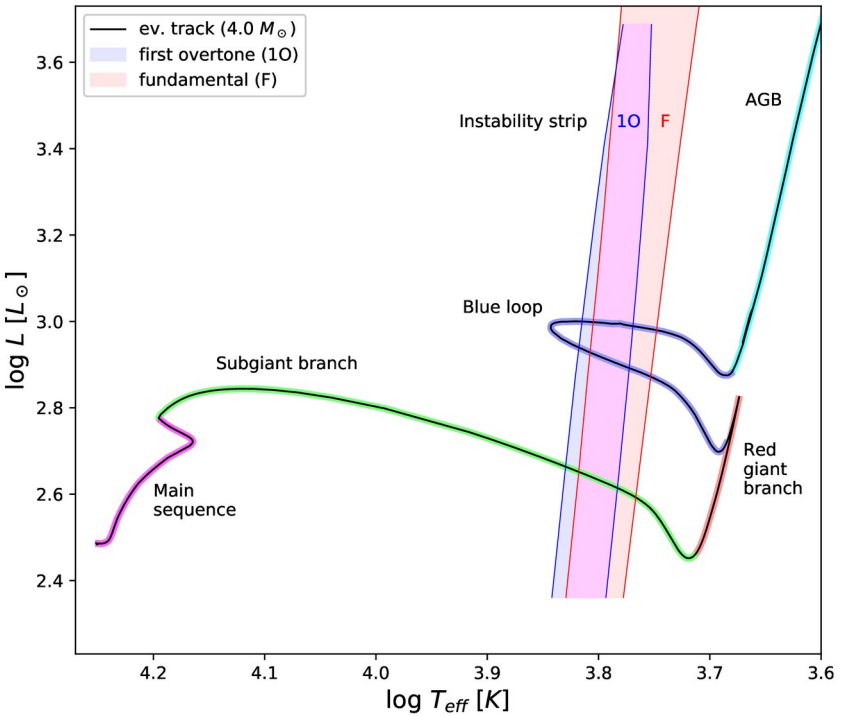


FIGURE 1

Do we understand them?

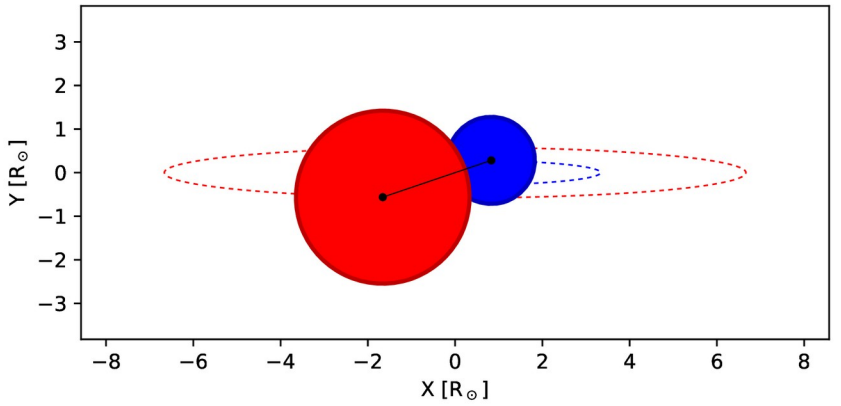
- **Theoretical studies:**
  - radially pulsating giants
  - instability strip (~5500-7000K)
  - predictions (masses 3–13 M_{sun})
- **Problems:**
  - lack of measurements
  - physical properties
    - esp. mass and radius
  - binarity / multiplicity
  - p-factor (for B-W methods)
  - Hubble tension – 5σ
    - Planck CMB vs. Cepheids+SNe

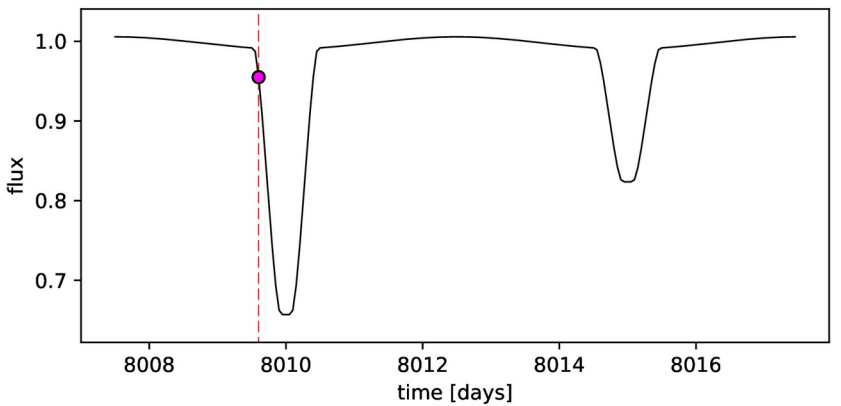
Evolutionary track for a typical Cepheid mass



Binary Cepheids

- Binarity of Cepheids: **80%** (Kervella+2019)
- Complications:
  - Companion's light
  - Orbital movement
- **Best tool** for determination of physical parameters
- **Eclipses**
  - Stellar radii
  - p-factor
- Lines of both components (SB2)
  - Accurate dynamical masses





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  - Stellar radii
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- Lines of both components (**SB2**)
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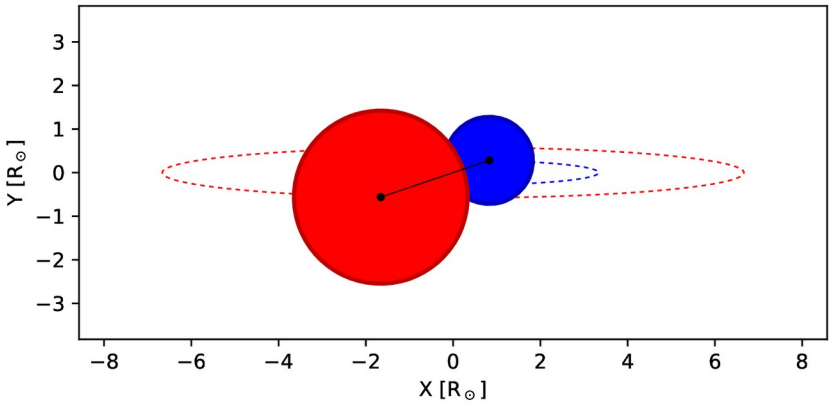
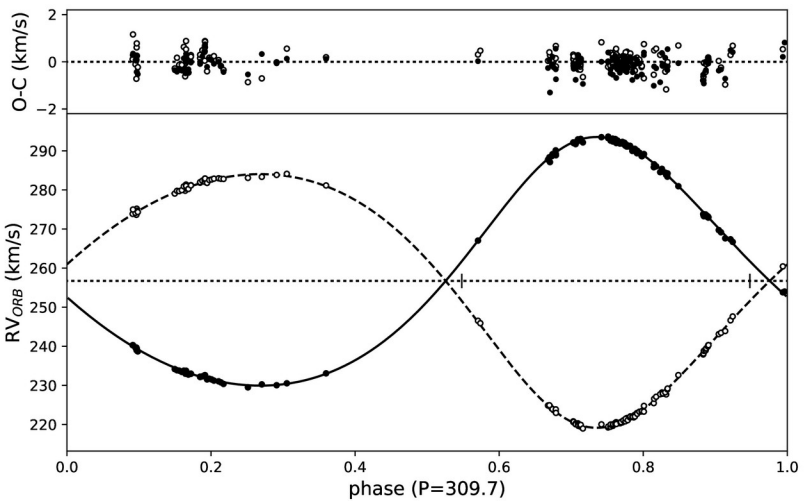




Introduction

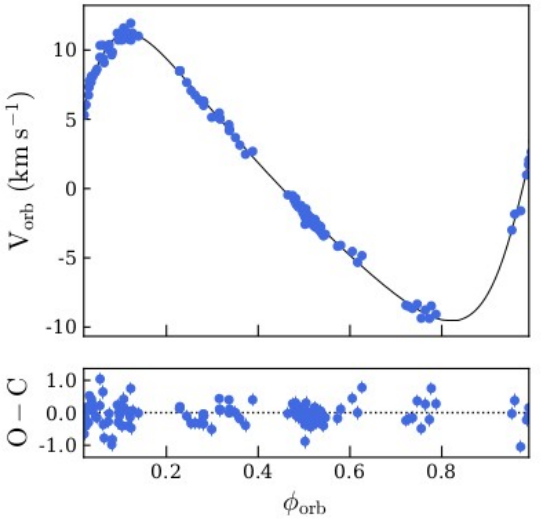
methods and binary types

Properties of Cepheids
SB1

- Cepheids in single-lined binaries
- Limited information
  - Mass function (minimum mass of the companion)

$$f(M_x, M_c) = \frac{(M_x \sin i)^3}{(M_x + M_c)^2}$$

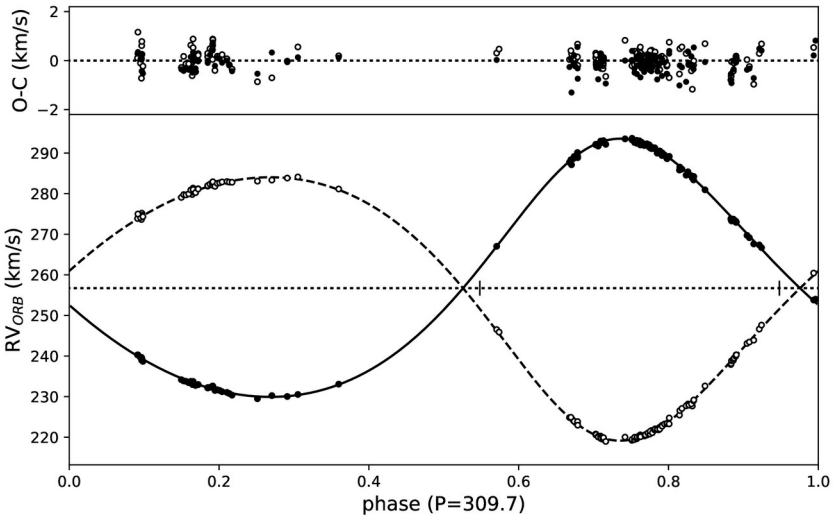
  - Inclination not known unless eclipsing or astrometric orbit measured
- If companion's properties known (e.g. from SED in UV)
  - Cepheid mass estimate (low precision and accuracy)

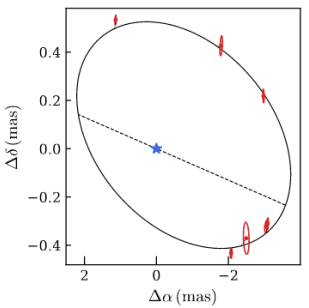


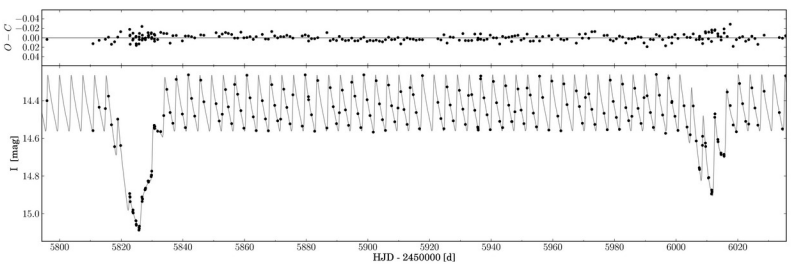
Properties of Cepheids

SB2

- Cepheids in double-lined binaries
- Mass ratio q = M_2 / M_1
- Minimum masses M_1,M_2 x $\sin^3(i)$
- Minimum separation A_1,A_2 x $\sin(i)$
- More information if:
  - Astrometric orbit
  - Eclipsing

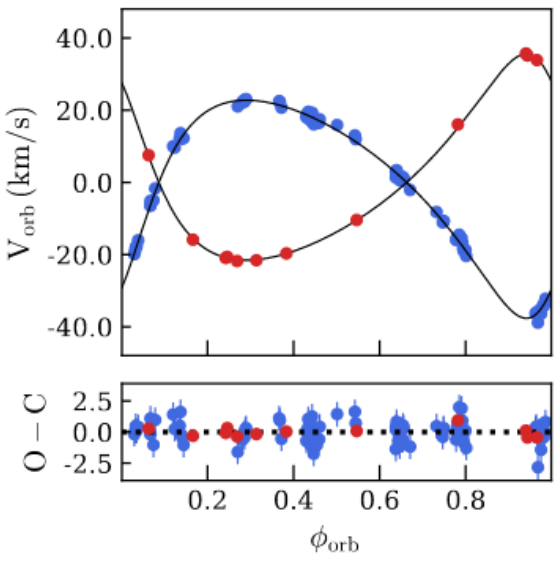






Properties of Cepheids

SB2 + astrometric orbit



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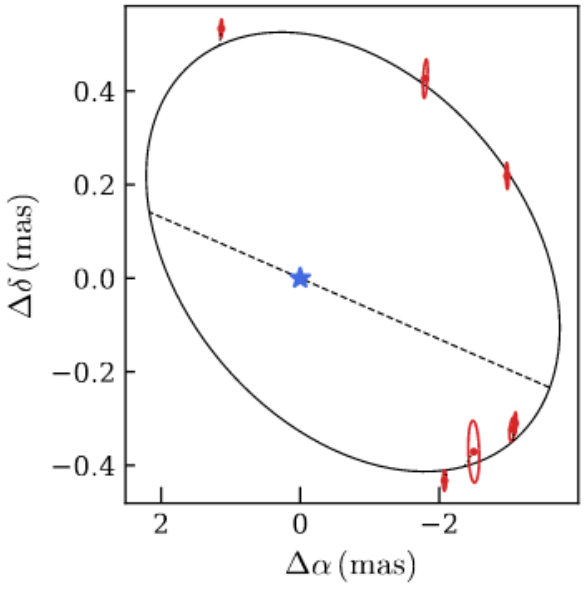

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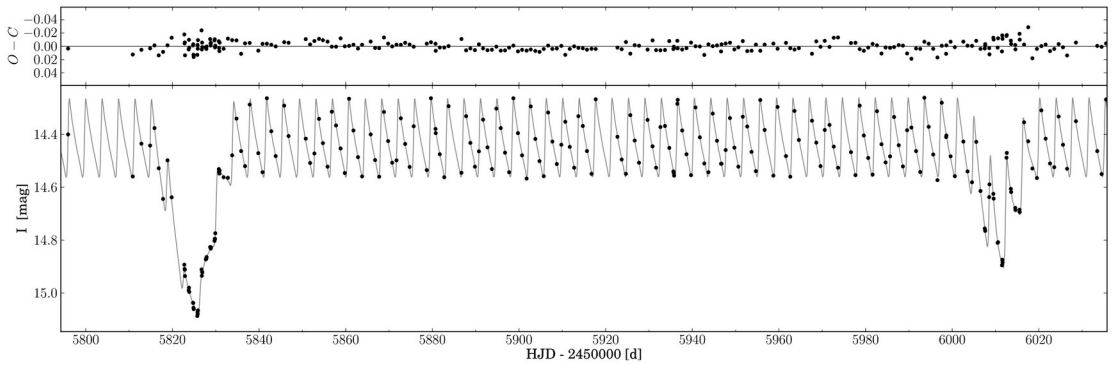
M_1, M_2

- Radii unknown (harder to compare with theoretical models)
- Eclipses not necessary

Properties of Cepheids

SB2 + eclipsing



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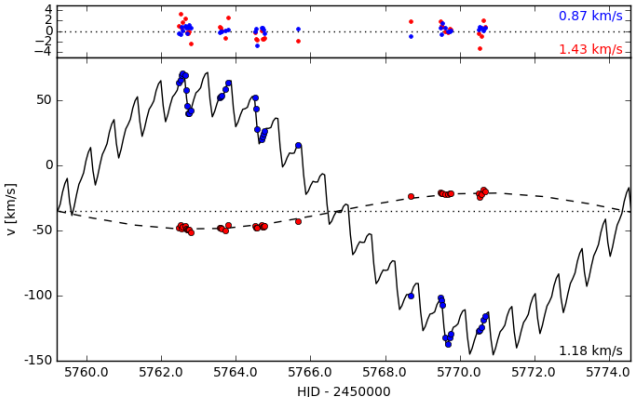

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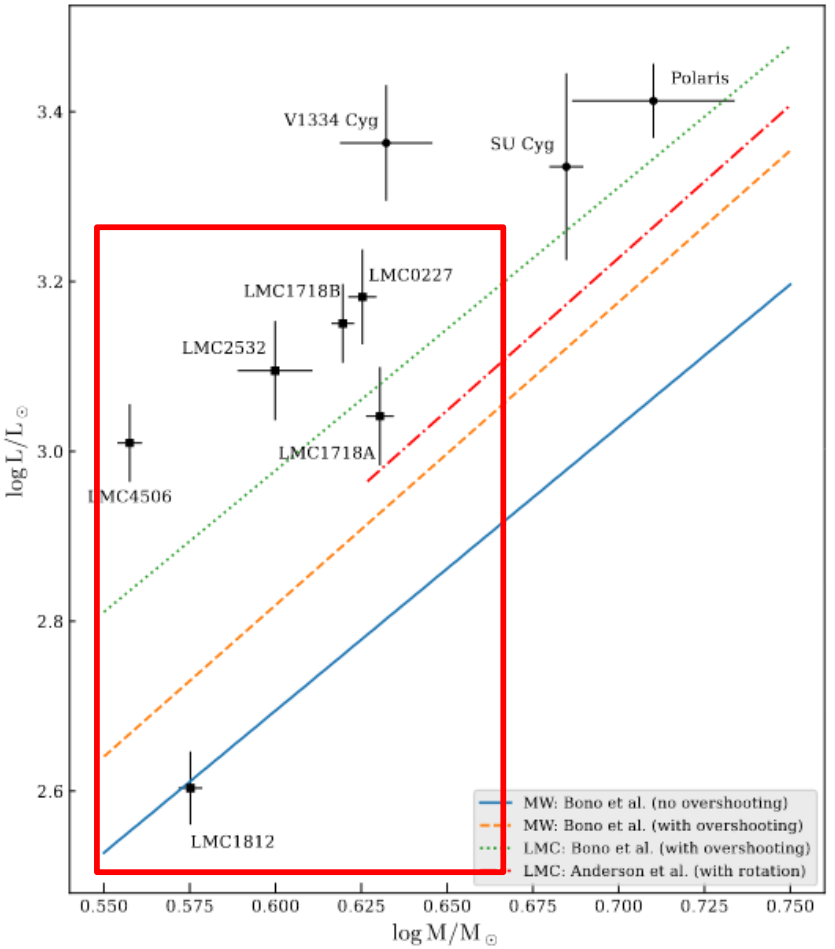
M_1, M_2
R_1, R_2

Binary Cepheids

- Important objects (distance determination, pulsation and evolution theory)
- About ~15000 known (Pietrukowicz+2021)
- Physical properties not well understood
- 6 accurate dynamical masses from 5 eclipsing SB2 systems (0.8-2.5%)
  - 3 new VIS+FUV SB2 + interf. (1.1-5.5%)
- Masses between 3.6-5 Msun
  - expected 3-13 Msun
- Mass – Luminosity relation poorly constrained (-Z)



Gallenne et al. (in prep.)

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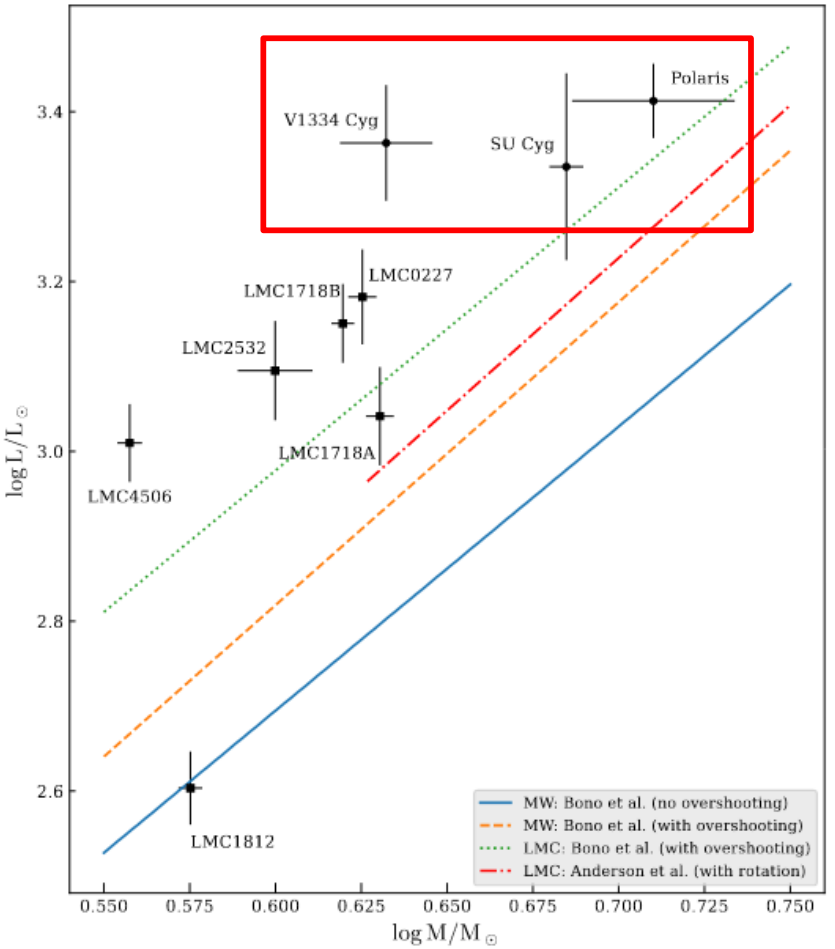


Gallenne et al. (in prep.)

Binary Cepheids

ID	mode	period [d]	mass [M⊙]	radius [R⊙]	T_{eff} [K]	p-factor	References
OGLE-LMC-CEP-4506	F	2.987846	3.61 ± 0.03	28.5 ± 0.2	6120 ± 160	1.35 ± 0.09	Pilecki+2018 Gieren+2015
OGLE-LMC-CEP-2532	1O	2.035349	3.98 ± 0.10	29.2 ± 1.4	6350 ± 150	-	Pilecki+2015 Pilecki+2018
OGLE-LMC-CEP-1812	F	1.312903	3.76 ± 0.03	17.85 ± 0.13	6120 ± 150	1.26 ± 0.08	Pilecki+2018
OGLE-LMC-CEP-1718B	1O	2.480917	4.22± 0.04	33.1 ± 1.3	6270 ± 160	-	Pilecki+2018 Gieren+2014
OGLE-LMC-CEP-1718A	1O	1.963663	4.27± 0.04	27.8 ± 1.3	6310 ± 150	-	Pilecki+2018 Gieren+2014
OGLE-LMC-CEP-0227	F	3.797086	4.165 ± 0.032	34.87 ± 0.12	6000 ± 160	1.21 ± 0.05	Pilecki+2013 Pilecki+2018
V350 Sgr	F	5.1542	5.2 ± 0.3	-	-	-	Evans+2018
V1334 Cygni	1O	3.33242	4.29 ± 0.13	-	-	1.30 ± 0.05	Gallene+2018
U Aql	F	7.02314	5.0 ± 0.6	-	-	-	Gallenne+2019
S Mus	F	9.66	4.6 ± 1.0 (6.0 ± 0.4)	-	-	-	Gallenne+2019 Evans+2006
RS Pup	F	41.43814	-	191	5060	1.25 ± 0.06	Kervella+2018
Polaris	1O	3.969251	5.13 ± 0.28 (3.5 ± 0.8)	-	-	-	Evans+2024 Evans+2008
AW Per	F	6.463635	6.79 ± 0.85	-	-	-	Evans+2024

MW & eclipsing LMC Cepheids
summary

MW Cepheids - binarity

László Szabados (konkoly.hu)

BINARIES AMONG GALACTIC CLASSICAL CEPHEIDS - MAIN TABLE

Cepheid	log P	<V>	Comp.	Dupl.	Remark	References
				status		
U_Aql	0.847	6.5	B9.8V	O	triple, ADS 12503	[Ab59][BP85][Ev92d][Ev95] [ECRKD05] [GKBMPGMSEABRK19] [Ll82] [Ma77][POP81][WELHBSM87]
FF_Aql	0.650	5.4	A9-F3V	O	triple, ADS 11884	[BMFBHPMBF07] [EWST90] [GKBMPGMSEABRK19] [G08] [GRS96] [GSBRS95][POP81][RGS97][UE93]
FN_Aql	0.977	8.4	-	B	-	[De77][Sz88][Us90][SzCsKCsDSzSBKJM14]
KL_Aql	0.786	10.2	-	B	-	[Pe78][Sz91]
V496_Aql	0.833	7.8	A1-A2	O	-	[Ev92a][G08][Sz89]
V916_Aql	1.128	10.8	-	B	-	[GSRS96]
V1344_Aql	0.874	7.8	-	B	-	[SzCsKCsDSzSBKJM14]
Eta_Aql	0.856	3.9	B9.8V	B	-	[BP85][Ev91]
V340_Ara	1.318	10.3	-	B	-	[SB03b]
RT_Aur	0.572	5.4	-	B:	-	[Tetal07]
RX_Aur	1.065	7.7	-	B	-	[GSRS96][MF80][Sz88]
YZ_Aur	1.260	10.4	-	B	-	[Ma77][MF80][SP98]
AN_Aur	1.012	10.5	-	B	-	[Ma77][Sz91]
AS_Aur	0.502	11.9	-	B	-	[SP98]
RW_Cam	1.215	8.7	-	B	-	[BP85][Ev94][Hip97][Ma77]
RX_Cam	0.898	7.7	-	O	-	[Ev95][GRS96][Im96][RGS97][Sz92a]
RY_CMa	0.670	8.1	-	B	-	[Vi91]
RZ_CMa	0.629	9.7	-	b	-	[Ma77][MF80][Pe78]
SS_CMa	1.092	9.9	-	B	-	[ACRMHSPBEMPR16] [EU94][Sz96]

- 171 Cepheids in the table

MW Cepheids - orbital elements

László Szabados (konkoly.hu)

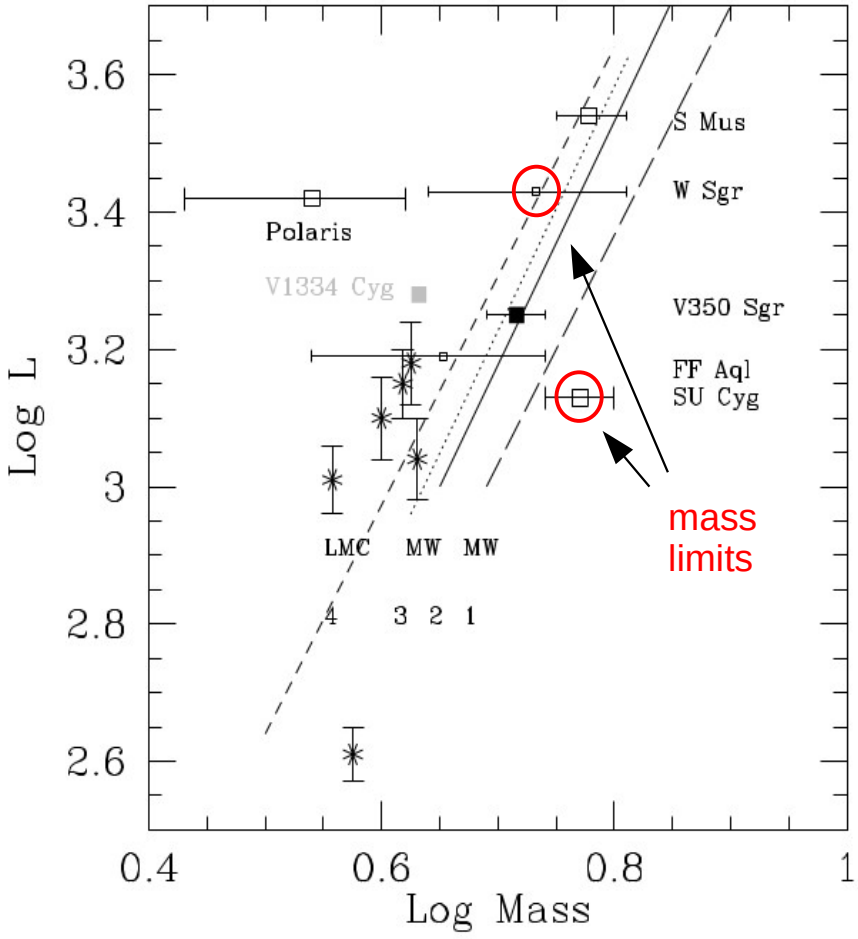
KNOWN ORBITAL ELEMENTS FOR BINARY CEPHEIDS

Cepheid	v_gamma [km/s]	K [km/s]	e	omega [degree]	T_0 JD	P_orb [day]	f(M) M_Sun	a sin i [million km]	Reference
U_Aql	1.31	8.41	0.193	167.1	2457575.3	1831.4	M_1=6.2+/-0.8	a=888.6+/-32.9	
	0.06	0.04	0.005	1.9	8.4	6.5		i=115.4+/-0.7 deg	[GKBMPGMSEABRK19]
U_Aql	1.15	7.81	0.165	190.5	2442754	1856.4	0.0881		
	0.15	0.22	0.027	7.7	38	4.3	0.0074	5.5	[WELHBSM87]
FF_Aql	-16.67	4.824	0.061	316.0	24458297.0	1430.3	0.0166	94.7	
	0.04	0.008	0.007	4.0	13.5	2.6	0.001	0.3	[GKBMPGMSEABRK19]
FF_Aql		4.91	0.027	319	2445437	1432.4			
		0.07	0.041	45	178	1.1			[G08]
FF_Aql			0.09	327	2453110.9	1434		a=679.2+/-20.9	
			0.01	4	14.6	1		i=33+/-5 deg	[BMFBHPMBF07]
FF_Aql	-15.8	5.1	0.0474	292	2445321	1434.2	0.02	100	
	0.14	0.12	0.05	45	173	1.0	0.001	3	[RGS97]
FF_Aql	-15.92	5.07	0.09	2.2	2445576.0	1429.72	0.0191	99.2	
	0.09	0.11	0.03	15.6	62.7	1.09	0.0013	2.2	[EWST90]
FF_Aql	-17.36	3.46	0.014	6.3	2425610.7	1435	0.0062	68.3	[Ab59]
FF_Aql	-16	5.0	0.09	327	2445381	1433	0.018		[GSBRS95]
V496_Aql		3.0	0	0	2445606	1331			
					25	6.5			[G08]

- 31 Cepheids in the table

Milky Way Cepheids

- Space observations
  - Nancy Evans+
  - Mass estimates from SB1
  - 6 Cepheids
    (incl. 2 mass limits)
- + interferometry
  - Alexandre Gallenne+
  - 4 Cepheids
    - 1 estimate from SB1
    - 3 precise masses
      from VIS+FUV SB2



Evans+2018

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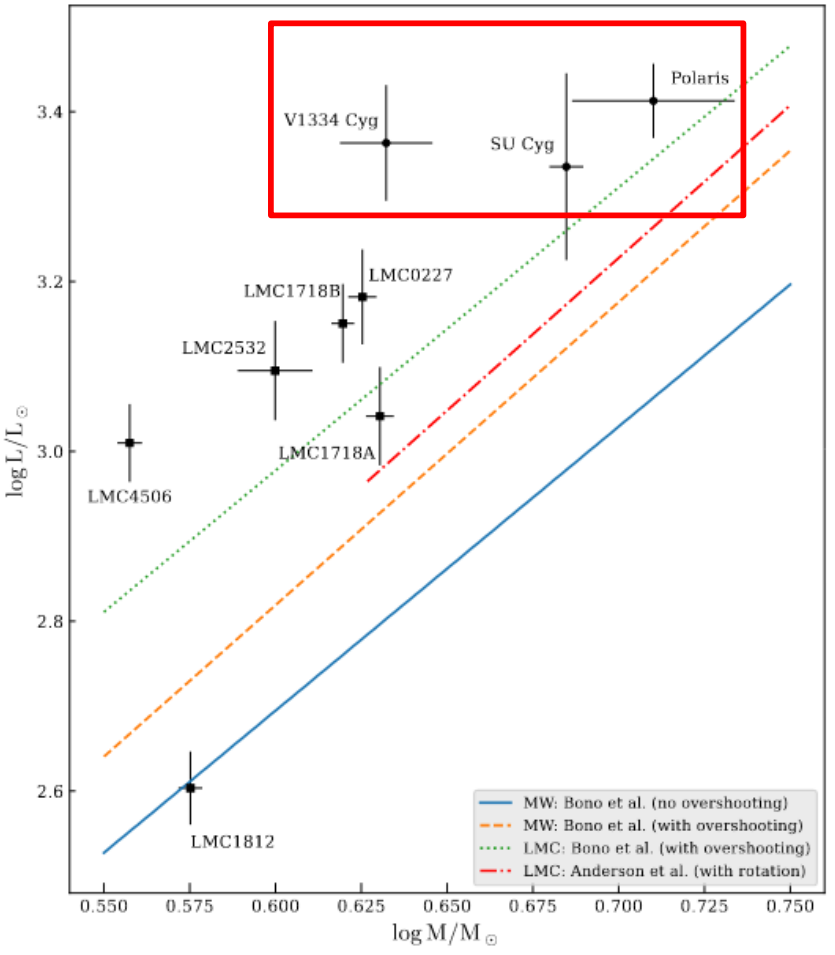


Gallenne et al. (in prep.)

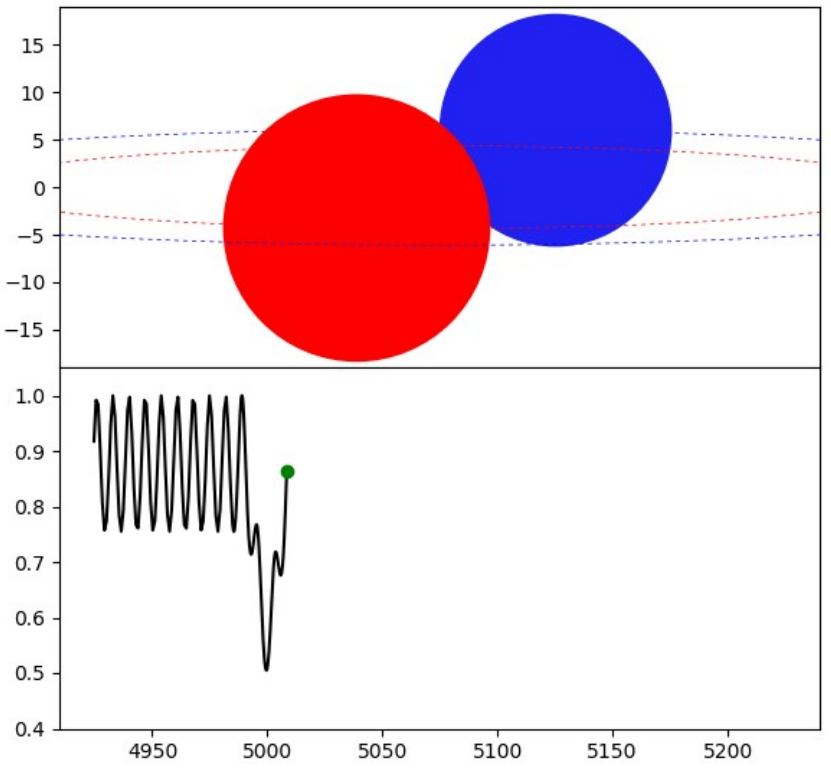
Eclipsing Cepheids in the LMC

a breakthrough - first dynamical mass measurement

- OGLE-LMC-CEP-0227
  (Pietrzyński+2010)
- FU classical Cepheid, P_{puls}=3.797d
- Orbital period: 309.7 d

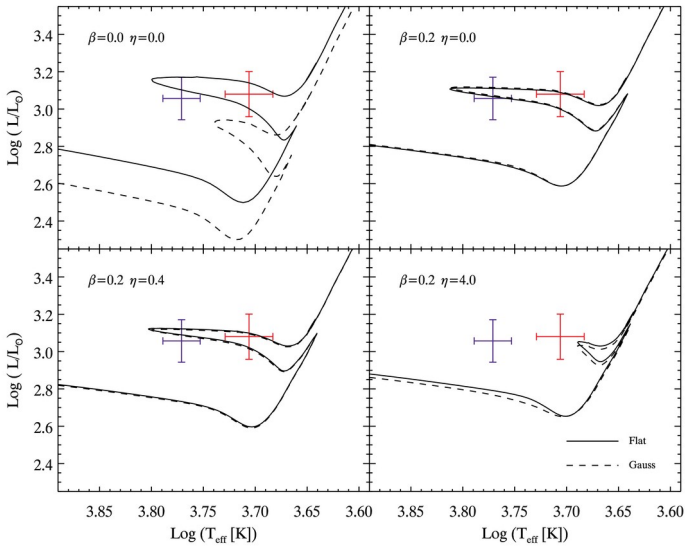
M_{cep} = 4.15(3) $M_\odot$
R_{cep} = 34.9(3) $R_\odot$
M_2 = 4.06(4) $M_\odot$
R_2 = 44.9(3) $R_\odot$

Dynamical	Pulsational	Evolutionary
4.15 ± 0.03	4.0 ± 0.3	4.5 - 5

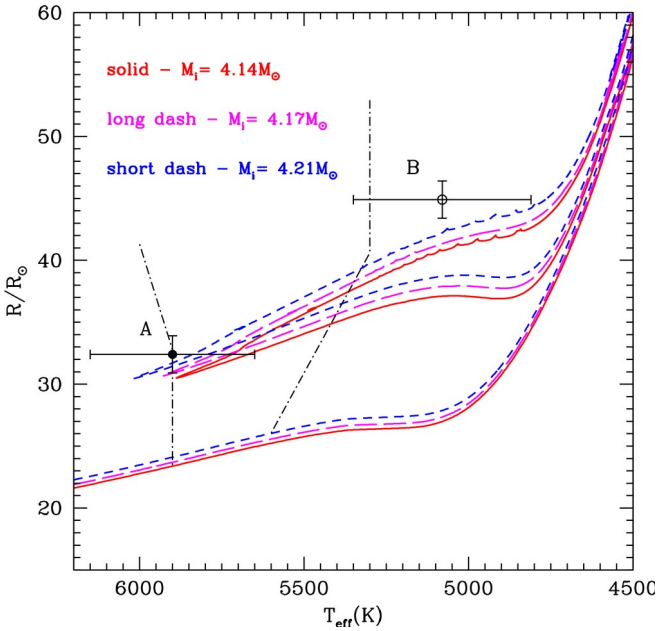


Eclipsing Cepheids in the LMC

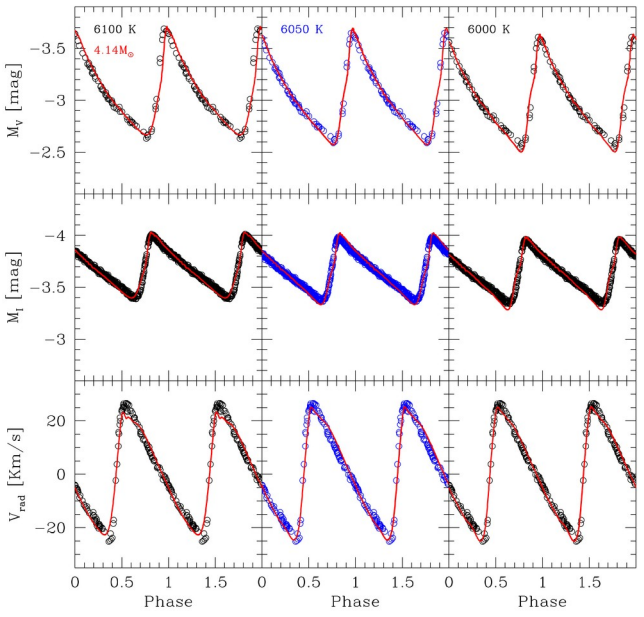
first dynamical mass (OGLE-LMC-CEP-0227)



Prada Moroni+2012



Cassisi & Salaris 2011



Marconi+2013

- Comparison with theoretical models

Eclipsing Cepheids in the LMC

accurate dynamical masses

- 6 Cepheids in 5 eclipsing SB2 systems
- 3 systems with almost perfect conditions for measurements
  - Masses precise ≥ 0.8%, radii to ≥ 0.3%
- 2 systems with only one eclipse per cycle

ID	T	PER	Mass	Radius	P-factor	Porb	Ecc.
CEP-0227	F	3.797086	4.15 (3)	34.9 (1)	1.21 (3)	309.669	0.1659
CEP-4506	F	2.987846	3.61 (3)	28.5 (2)	1.35 (9)	1550.354	0.6116
CEP-2532*	FO	2.035349	3.98 (10)	29.2 (14)	---	800.419	0.3075
CEP-1718B*	FO	2.480917	4.22 (4)	33.1 (13)	---	412.807	0.276
CEP-1718A*	FO	1.963663	4.27 (4)	27.8 (12)	---	412.807	0.276
CEP-1812	F	1.312903	3.76 (6)	17.85(13)	1.26 (8)	551.797	0.129

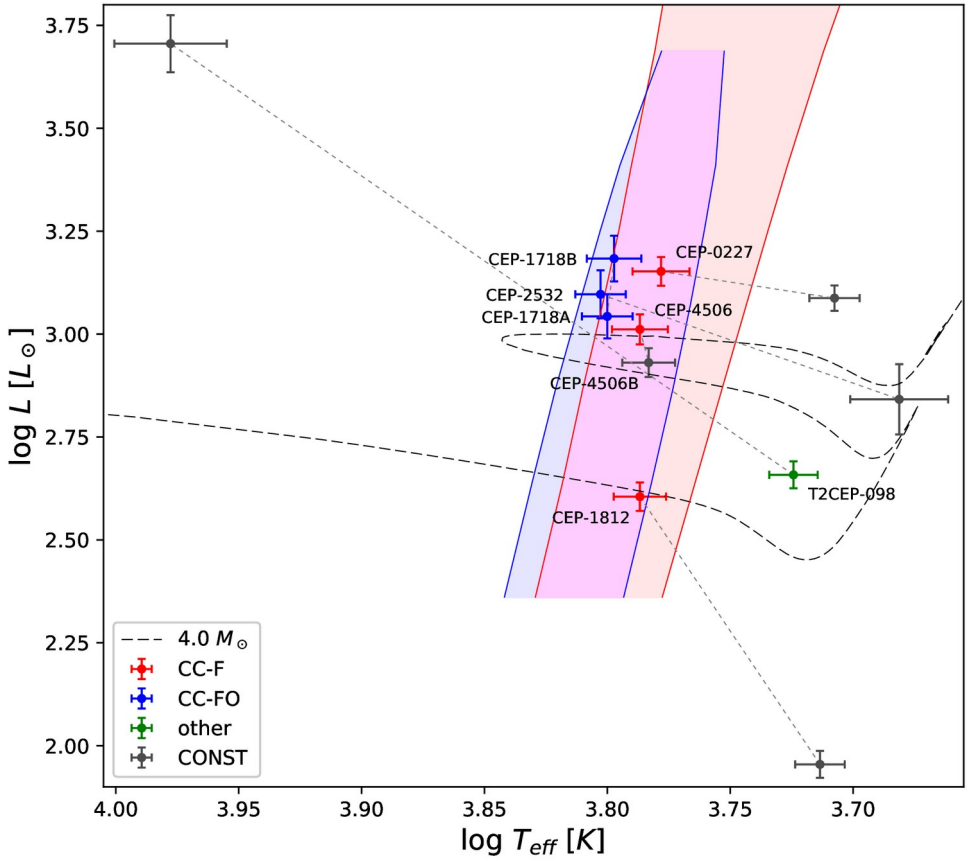
* one eclipse per cycle

Pilecki+2018

Eclipsing Cepheids in the LMC

other results

- First direct p-factor determination
- 3 measured p-factors
- Merger-origin Cepheid
- System composed of two Cepheids
- Non-pulsating star inside IS
- Empirical P-M-R relation



Pilecki+2018

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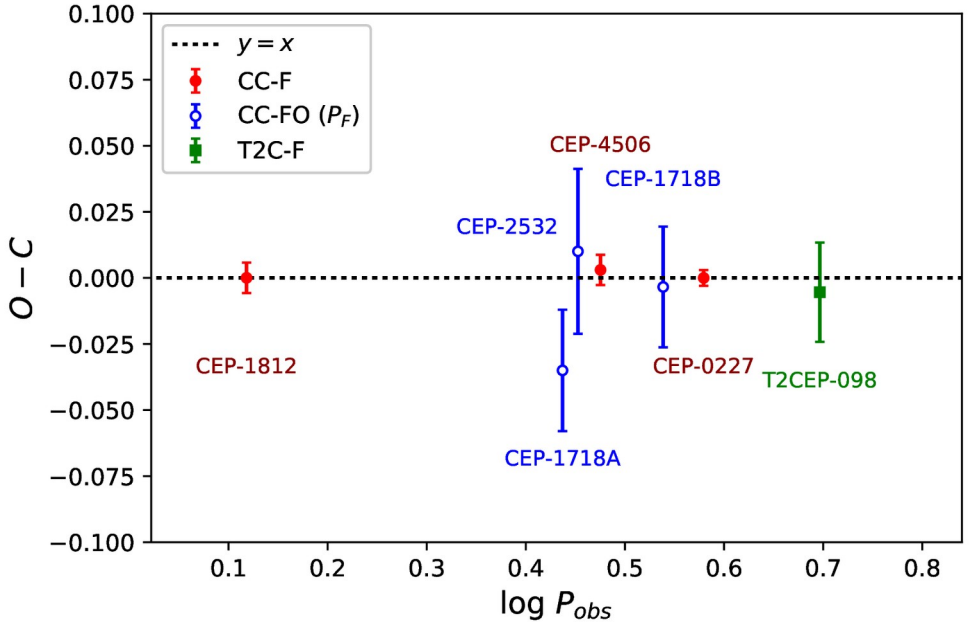
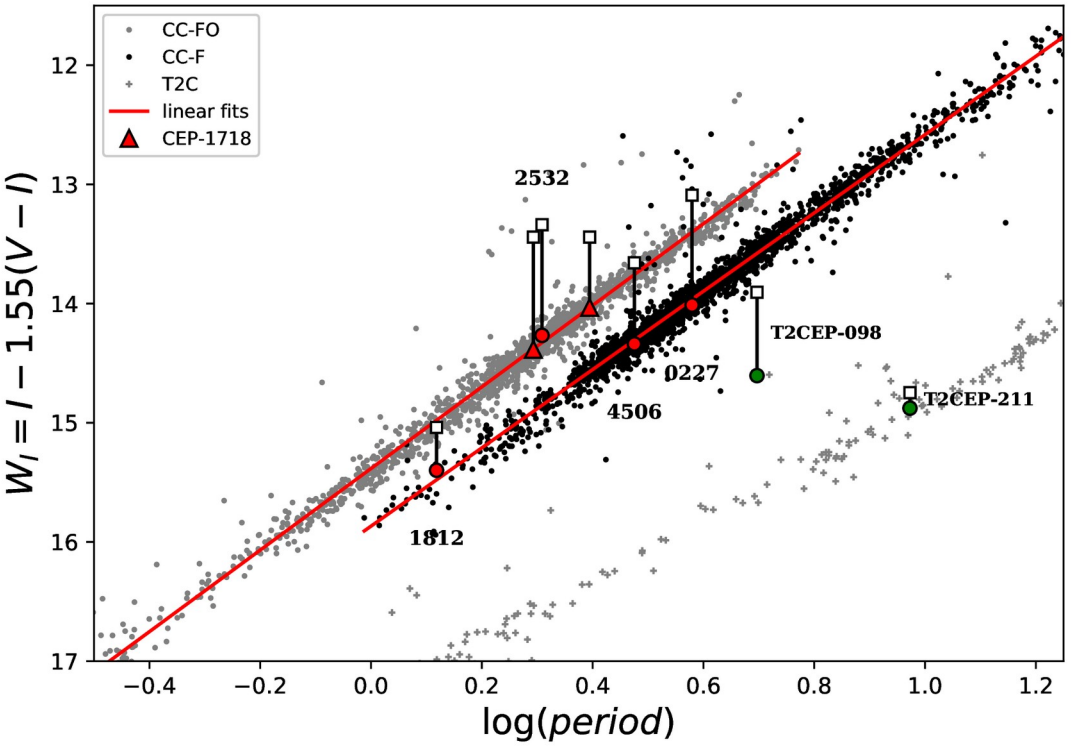


log $\boldsymbol{P_{MR}}$ = –1.56 (4) – 0.80 (4) log $\boldsymbol{M}$ + 1.70 (3) log $\boldsymbol{R}$

And not P ~ $M^{-0.5}$ * $R^{1.5}$
(period-density relation)

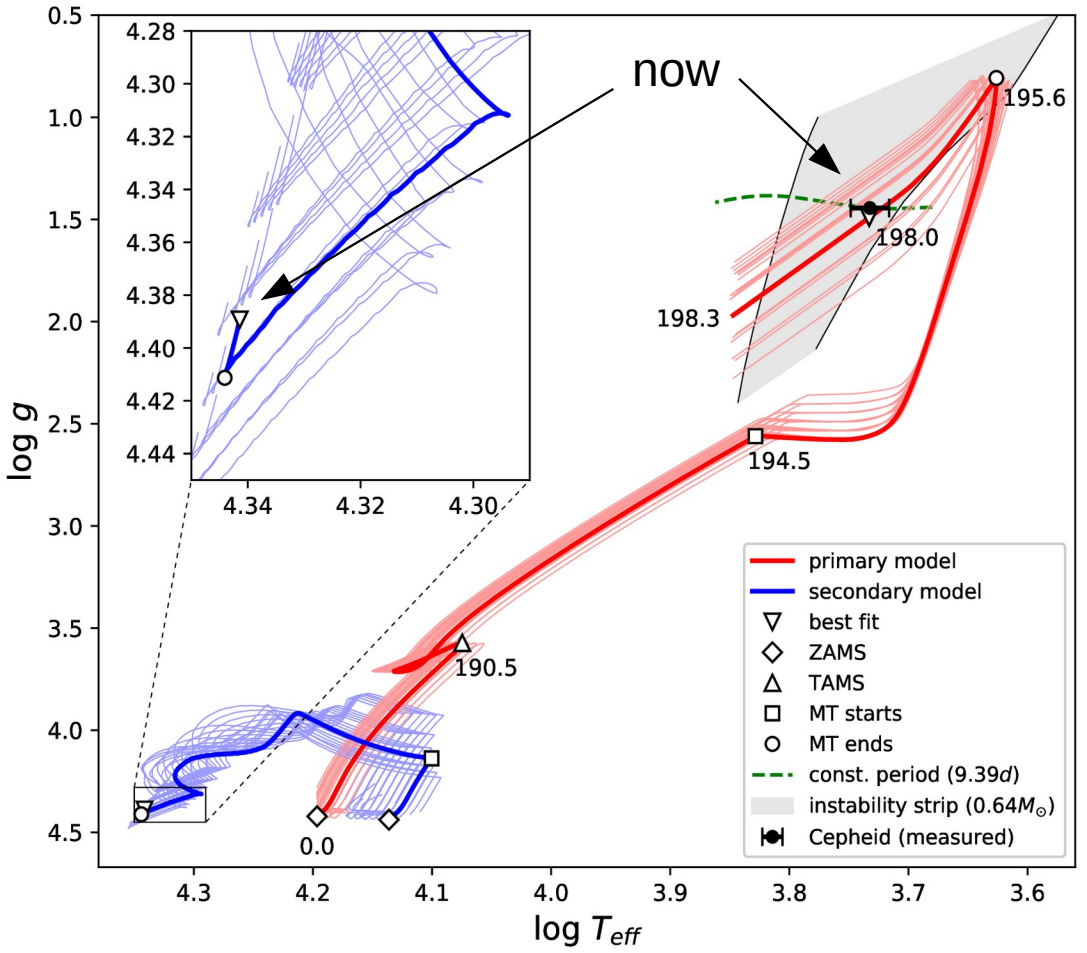
Type II Cepheids
in binary systems

- First mass measurements for pW Vir stars
  - T2CEP-098 1.5 $M_\odot$
  - T2CEP-211 0.64 $M_\odot$
- Origin of pW stars
- Disks around companions



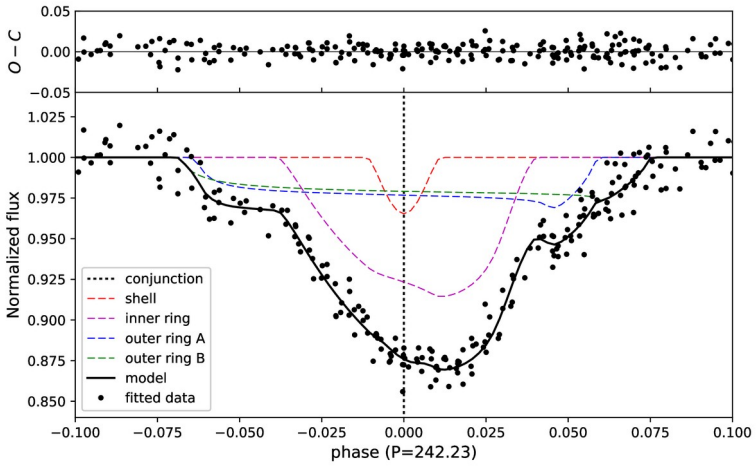
Type II Cepheids
in binary systems

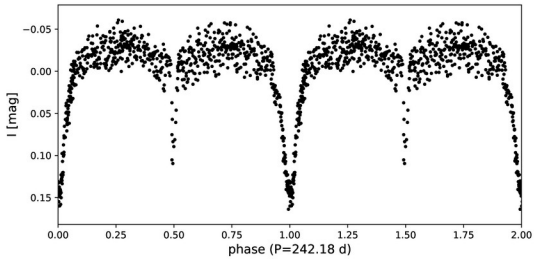
- First mass measurements for pW Vir stars
  - T2CEP-098 1.5 $M_\odot$
  - T2CEP-211 0.64 $M_\odot$
- Origin of pW stars
  - From binary evolution
  - Young objects
- Disks around companions

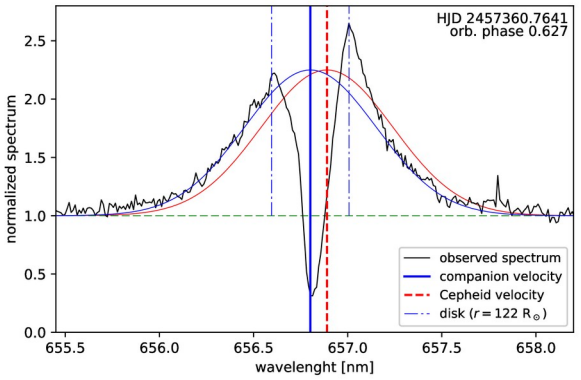


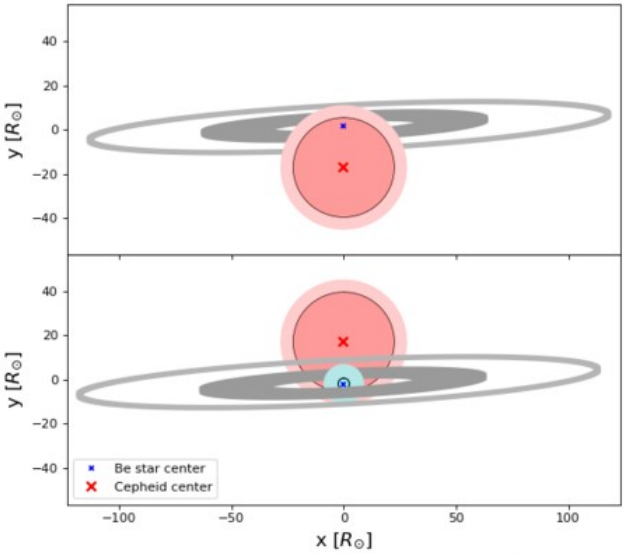
Relatively young objects (not population II) !

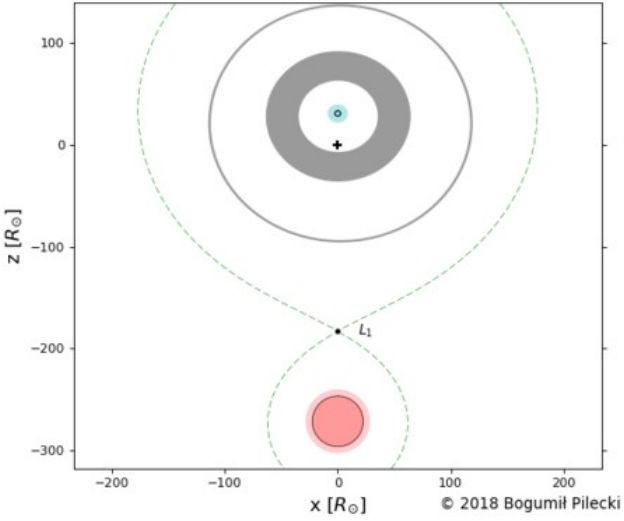
Type II Cepheids
in binary systems











- Disks around companions
  - Complex structure

Cepheids with giant companions

The Astrophysical Journal, 910:118 (9pp), 2021 April 1 https://doi.org/10.3847/1538-4357/abe7e9

Cepheids with Giant Companions. I. Revealing a Numerous Population of Double-lined Binary Cepheids*†

Bogumił Pilecki[1], Grzegorz Pietrzyński[1], Richard I. Anderson[2,3], Wolfgang Gieren[4], Mónica Taormina[1], Weronika Narloch[4], Nancy R. Evans[5], and Jesper Storm[6]
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Received 2021 January 20; revised 2021 February 15; accepted 2021 February 17; published 2021 April 5

Abstract

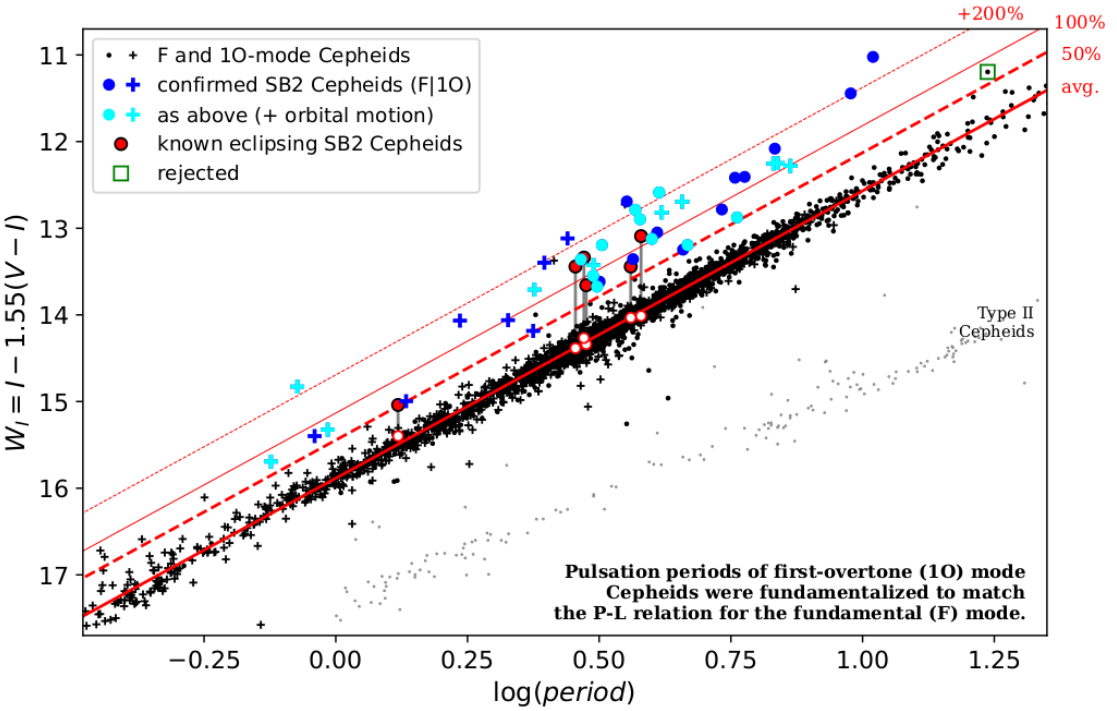
Masses of classical Cepheids of 3–11 $M_{\odot}$ are predicted by theory but those measured clump between 3.6–5 $M_{\odot}$. As a result, their mass–luminosity relation is poorly constrained, impeding our understanding of basic stellar physics and the Leavitt Law. All Cepheid masses come from the analysis of 11 binary systems, including only five that are double lined and well suited for accurate dynamical mass determination. We present a project to analyze a new, numerous group of Cepheids in double-lined binary (SB2) systems to provide mass determinations in a wide mass interval and study their evolution. We analyze a sample of 41 candidate binary LMC Cepheids spread along the *P–L* relation, which are likely accompanied by luminous red giants, and present indirect and direct indicators of their binarity. In a spectroscopic study of a subsample of 18 brightest candidates, for 16 we detected lines of two components in the spectra, already quadrupling the number of Cepheids in SB2 systems. Observations of the whole sample may thus lead to quadrupling all the Cepheid mass estimates available now. For the majority of our candidates, erratic intrinsic period changes dominate over the light-travel-time effect due to binarity. However, the latter may explain the periodic phase modulation for four Cepheids. Our project paves the way for future accurate dynamical mass determinations of Cepheids in the LMC, Milky Way, and other galaxies, which will potentially increase the number of known Cepheid masses even 10-fold, hugely improving our knowledge about these important stars.

Unified Astronomy Thesaurus concepts: Cepheid variable stars (218); Delta Cepheid variable stars (368); Spectroscopic binary stars (1557); Late-type giant stars (908)

Cepheids with giant companions

the project and current status

- Pilot program 2020:
  - 16 new Cepheids in SB2 (LMC) (3x before)
  - Higher periods/masses
  - P-L outlier Cepheids explained
- Observations 2021-2024
- Current status:
  - 60 Cepheids in SB2 (LMC/SMC/MW) (10x before)
  - 37 with orbital motion (final proof)
  - 24 with preliminary orbital solutions (P_{orb}, $M^* sin^3(i)$, $q = M_2 / M_1$, ...)



Cepheids with giant companions

example orbital RV curves

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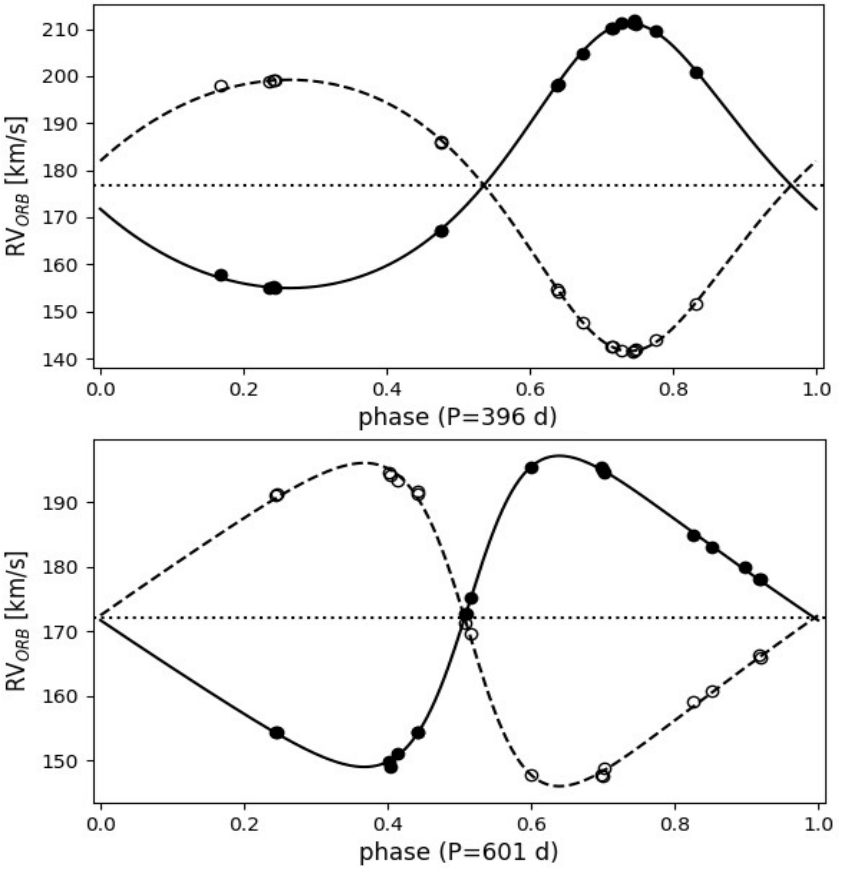

Cepheids with giant companions
minimum masses

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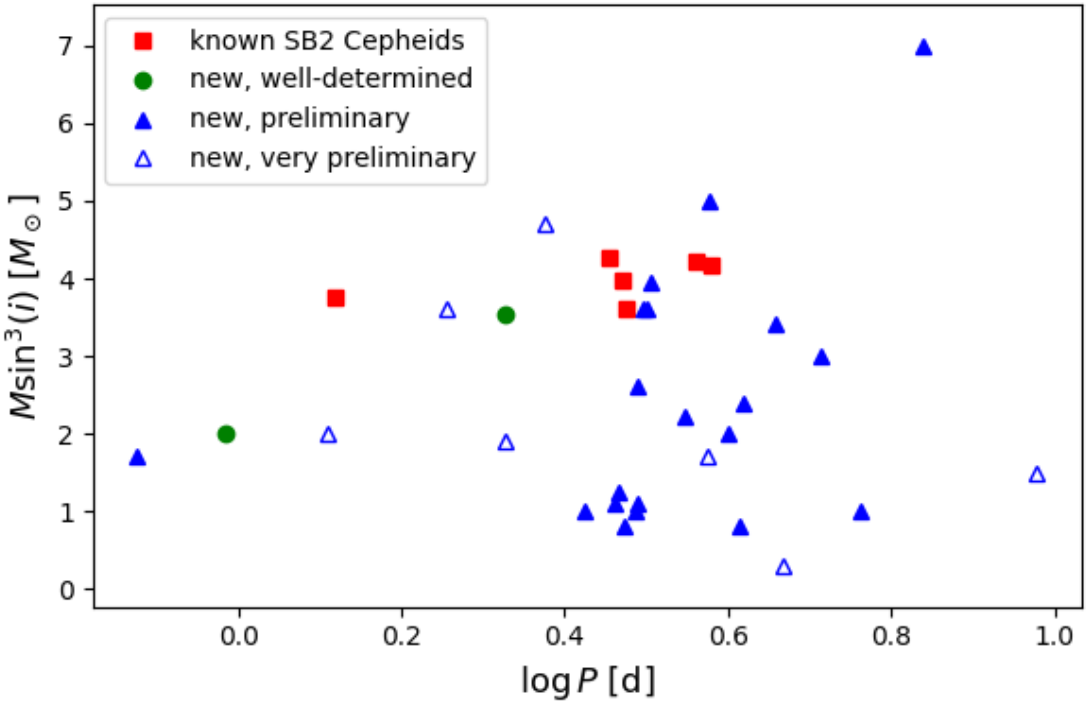

Cepheids with giant companions

merger-origin Cepheids

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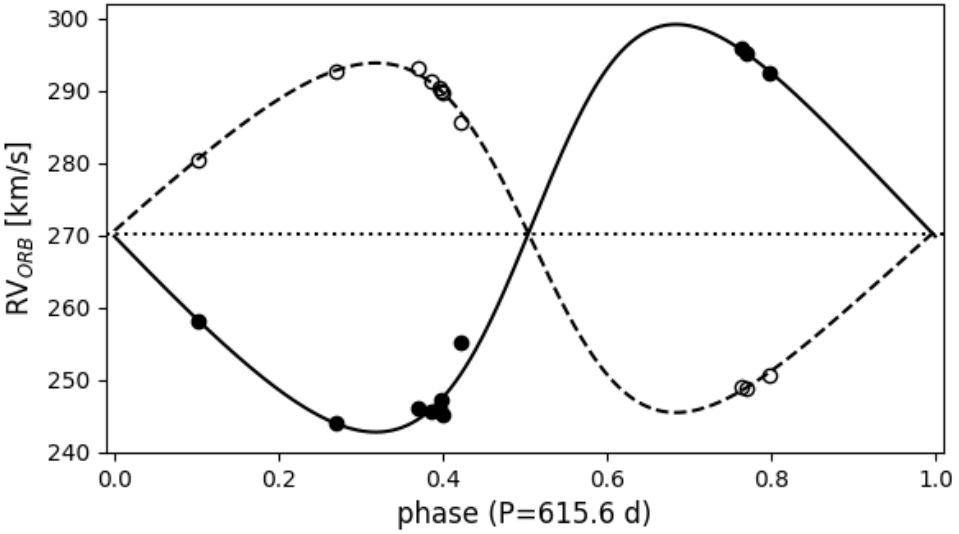

- **Merger-origin binary Cepheids**
  (several with q != 1.0)
  - Cepheid or companion
  - From triple (multiple) systems

Cepheids with giant companions
wide-orbit binaries

- Pilot program 2020:
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  - Higher periods/masses
  - P-L outlier Cepheids explained
- Observations 2021-2024
- Current status:
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  - 37 with orbital motion (final proof)
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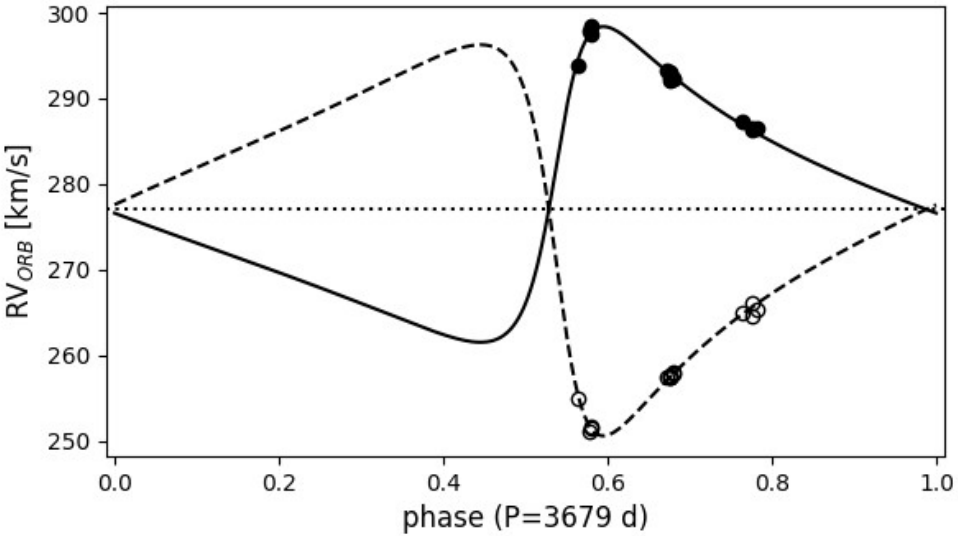

- **Wide-orbit binaries**
  - long orbital periods
  - best candidates for direct geometrical distances

The Astrophysical Journal Letters, 940:L48 (5pp), 2022 December 1 https://doi.org/10.3847/2041-8213/ac9fcc

Discovery of a Binary-origin Classical Cepheid in a Binary System with a 59 day Orbital Period*†

Bogumił Pilecki[1], Ian B. Thompson[2], Felipe Espinoza-Arancibia[1], Richard I. Anderson[3], Wolfgang Gieren[4], Weronika Narloch[4], Javier Minniti[1], Grzegorz Pietrzyński[1], Mónica Taormina[1], Giuseppe Bono[5], and Gergely Hajdu[1]
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Received 2022 September 24; revised 2022 October 31; accepted 2022 November 1; published 2022 November 30

Abstract

We report the discovery of a surprising binary configuration of the double-mode Cepheid OGLE-LMC-CEP-1347 pulsating in the first ($P_1 = 0.690$ days) and second-overtone ($P_2 = 0.556$ days) modes. The orbital period ($P_{\rm orb} = 59$ days) of the system is five times shorter than the shortest known to date (310 days) for a binary Cepheid. The Cepheid itself is also the shortest-period one ever found in a binary system and the first double-mode Cepheid in a spectroscopically double-lined binary. OGLE-LMC-CEP-1347 is most probably on its first crossing through the instability strip, as inferred from both its short period and fast period increase, consistent with evolutionary models, and from the short orbital period (not expected for binary Cepheids whose components have passed through the red giant phase). Our evolutionary analysis yielded a first-crossing Cepheid with a mass in a range of 2.9–3.4 $M_{\odot}$ (lower than any measured Cepheid mass), consistent with observations. The companion is a stable star, at least two times fainter and less massive than the Cepheid (preliminary mass ratio $q = 0.55$), while also redder and thus at the subgiant or more advanced evolutionary stage. To match these characteristics, the Cepheid has to be a product of binary interaction, most likely a merger of two less massive stars, which makes it the second known classical Cepheid of binary origin. Moreover, further evolution of the components may lead to another binary interaction.

Unified Astronomy Thesaurus concepts: Cepheid variable stars (218); Double-mode Cepheid variable stars (402); Spectroscopic binary stars (1557); Late-type stars (909)

OGLE LMC-CEP-1347

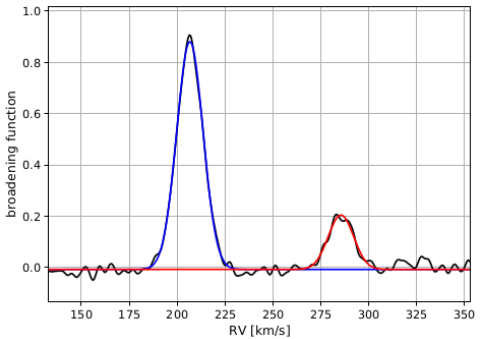
a merger-origin, first-crossing, low-mass 1O/2O Cepheid

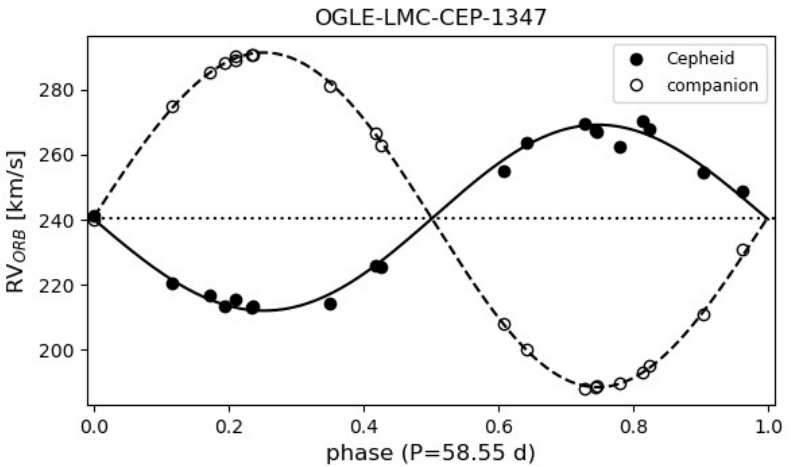
(Pilecki 2022, ApJL, 940, 48)

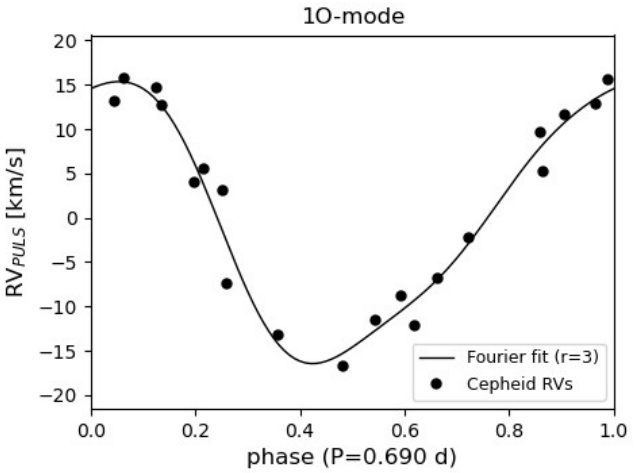
Cepheids with giant companions

OGLE-LMC-CEP-1347

- Orbital period: 59 days (!)
- 5 times shorter than any measured before (310 d)
- Expected periods > 200 days (after RGB) (Neilson+2015)
- Cepheid ~2x more massive
- Companion fainter and redded







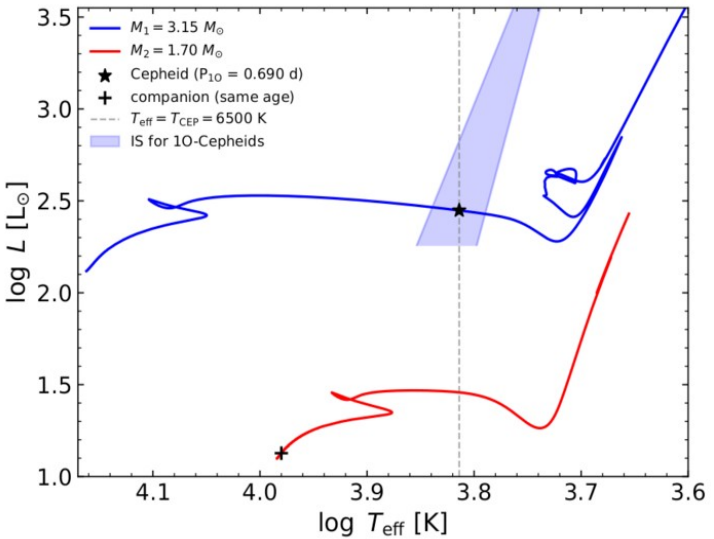
Pilecki+2022 (updated)

Cepheids with giant companions

OGLE-LMC-CEP-1347

- $M_{cep} > 2.02\ M_\odot$
- $M_{comp} > 1.12\ M_\odot$
- Estimates:
  - $M_{cep} \sim 3.2\ M_\odot$
  - $M_{comp} \sim 1.8\ M_\odot$
- => merger-origin Cepheid
  - 2+1 → 1+1
- => Hertzsprung gap (first crossing)
- See talk by Felipe Espinoza (new analysis and results)

Parameter	Value	Unit
P	58.85 ± 0.08	days
T_0 (HJD)	2459050.0 ± 0.7	days
$a \sin i$	93.2 ± 1.0	$R_\odot$
$m_1 \sin^3 i$	2.02 ± 0.04	$M_\odot$
$m_2 \sin^3 i$	1.12 ± 0.06	$M_\odot$
$q = m_2/m_1$	0.553 ± 0.016	-
e	0.0	-



A&A, 686, A263 (2024)
https://doi.org/10.1051/0004-6361/202349138

Astronomy & Astrophysics

Cepheids with giant companions

II. Spectroscopic confirmation of nine new double-lined binary systems composed of two Cepheids★,★★

Bogumił Pilecki[1], Ian B. Thompson[2], Felipe Espinoza-Arancibia[1], Gergely Hajdu[1], Wolfgang Gieren[3], Mónica Taormina[1], Grzegorz Pietrzyński[1], Weronika Narloch[1], Giuseppe Bono[4], Alexandre Gallenne[5,6], Pierre Kervella[7], Piotr Wielgórski[1], Bartłomiej Zgirski[3], Dariusz Graczyk[8], Paulina Karczmarek[3], and Nancy R. Evans[9]

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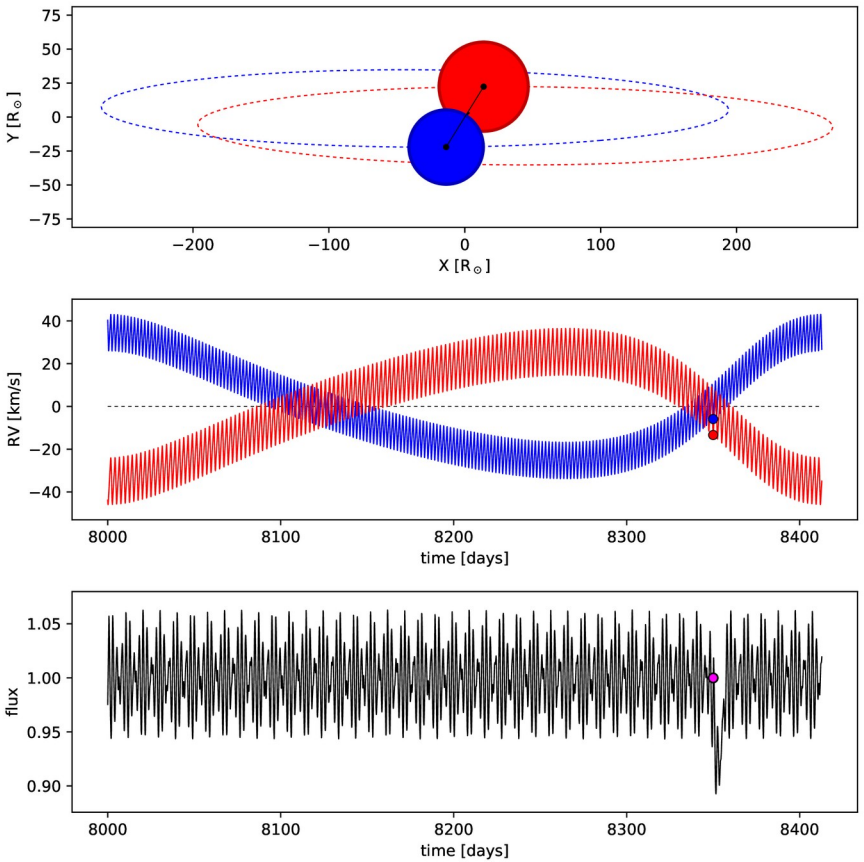
BIND Cepheids

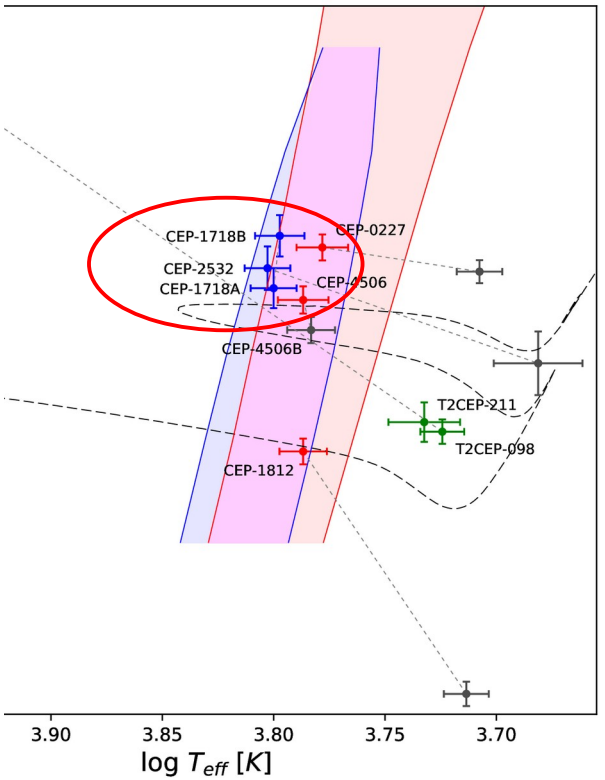
Spectroscopic confirmation of 9 new binary double Cepheids

(Pilecki 2024, A&A, 686, 263)

Binary Double (BIND) Cepheids

eclipsing LMC-CEP-1718





Gieren+2014, Pilecki+2018

Binary Double (BIND) Cepheids

eclipsing LMC-CEP-1718

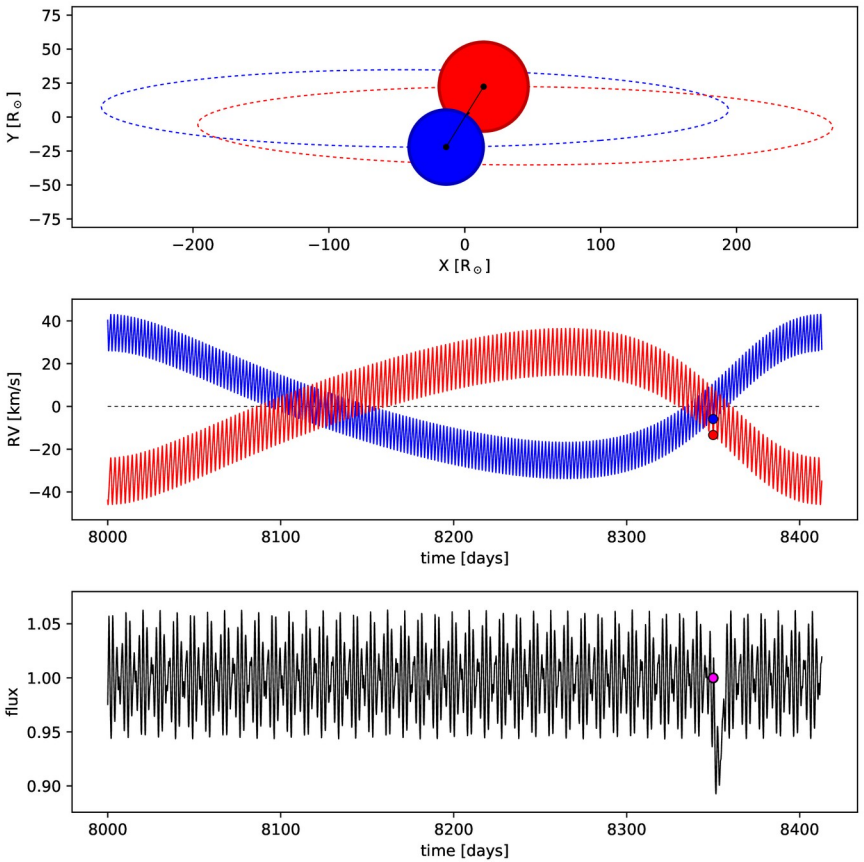


Table 3
Properties of OGLE LMC-CEP-1718

Parameter	Primary	Secondary	Unit
spectral type	F5 II	F6 II/Ib	···
pulsation period	1.9636625	2.480917	days
mass	4.27 ± 0.04	4.22 ± 0.04	$M_\odot$
radius[a]	27.8 ± 1.2	33.1 ± 1.3	$R_\odot$
$\log g$	2.18 ± 0.04	2.02 ± 0.03	cgs
temperature	6310 ± 150	6270 ± 160	K
$\log L/L_\odot$	3.04 ± 0.06	3.18 ± 0.06	···
V	15.72 ± 0.03	15.74 ± 0.03	mag
$(V-I)$	0.51 ± 0.02	0.52 ± 0.02	mag
orbital period	412.813 ± 0.008		days
T_{sec}	2456701.77 ± 0.05		days
semimajor axis	476.1 ± 1.2		$R_\odot$
inclination	83.0 ± 0.5		degrees
R_1+R_2	60.9 ± 1.5		$R_\odot$
R_2/R_1[b]	1.19 ± 0.08		···
$E(B-V)$	0.125 ± 0.015		mag

Pilecki+2018

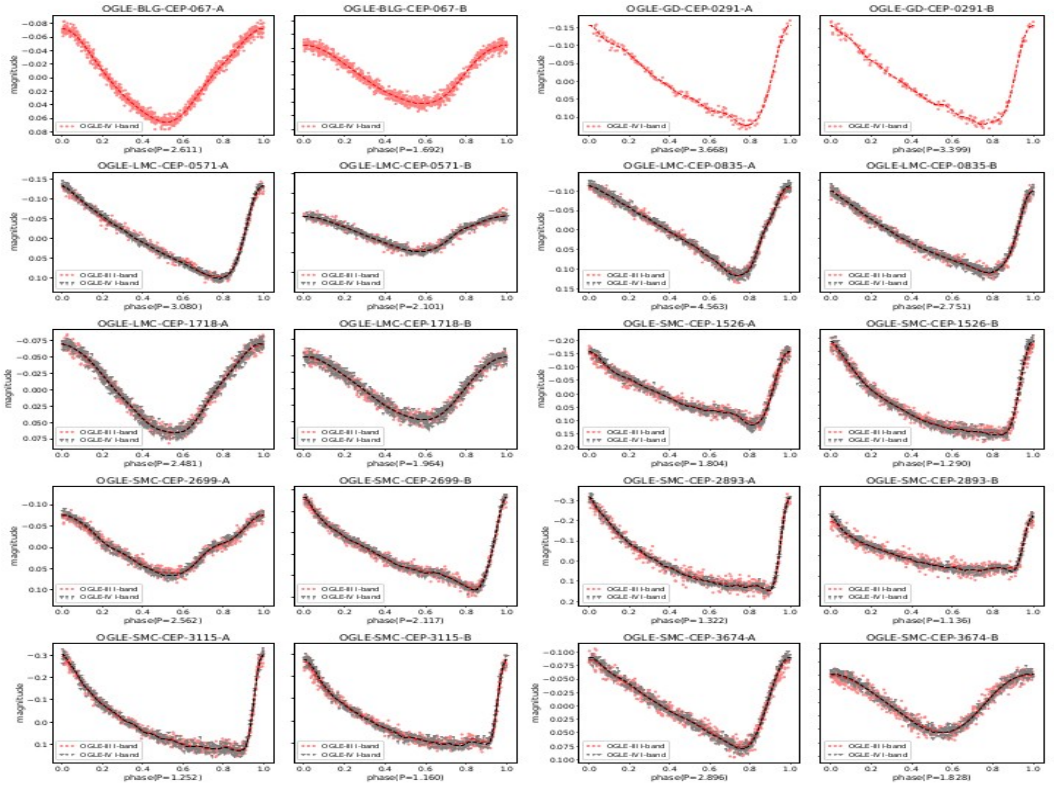
$P_1/P_2 \sim 0.79$

$M_1/M_2 \sim 1.01$

Binary Double (BIND) Cepheids

the sample

OGLE ID	modes
BLG-CEP-067	1O+1O
GD-CEP-0291	F+F
LMC-CEP-0571	F+1O
LMC-CEP-0835	F+F
LMC-CEP-1718	1O+1O
SMC-CEP-1526	F+F
SMC-CEP-2699	1O+F
SMC-CEP-2893	F+F
SMC-CEP-3115	F+F
SMC-CEP-3674	F+1O



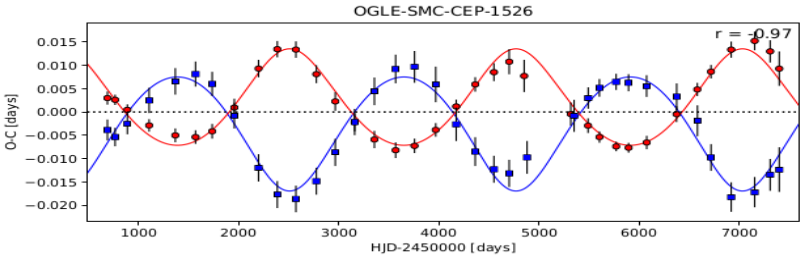
Candidate double Cepheids:

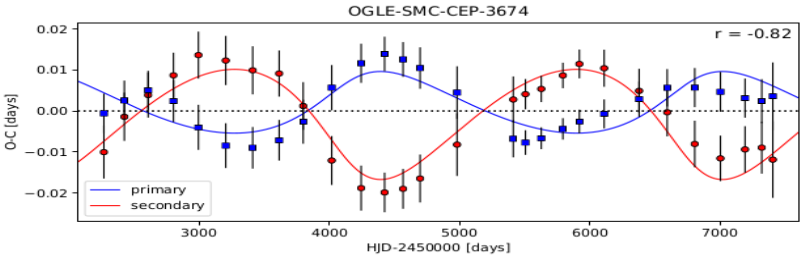
- LMC: 2
- SMC: 5
- MW: 2

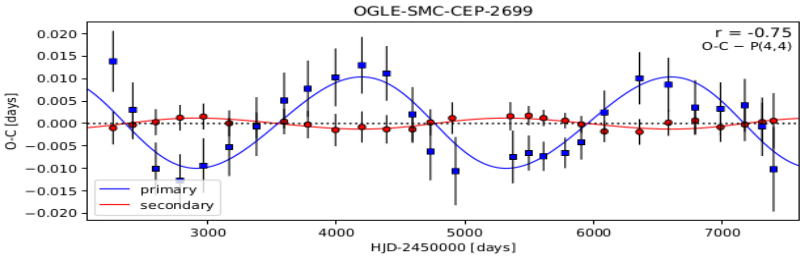
BIND Cepheids

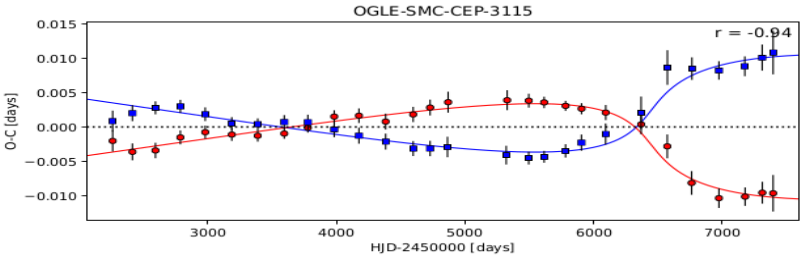
binary O-C diagrams

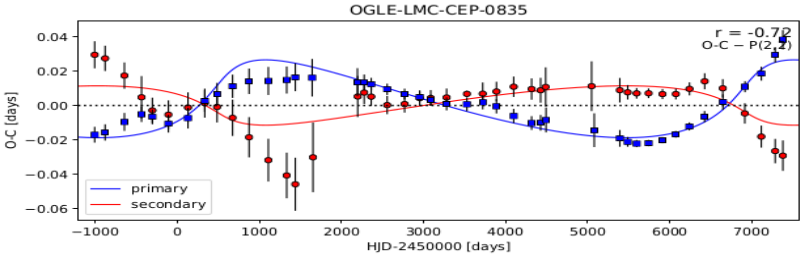
- **O-C for both components combined**
- Polynomial subtraction
- Looking for r < -0.7
- anticorrelated light-travel time effect
- binarity proof for 5 double Cepheids

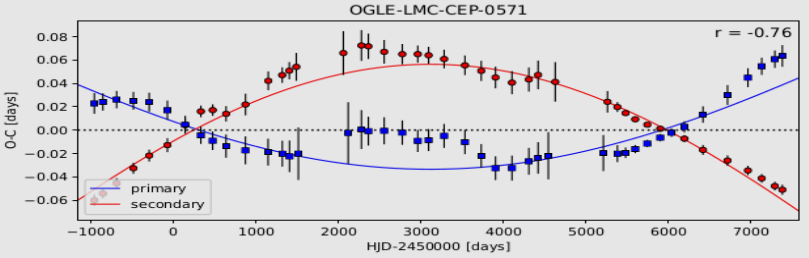






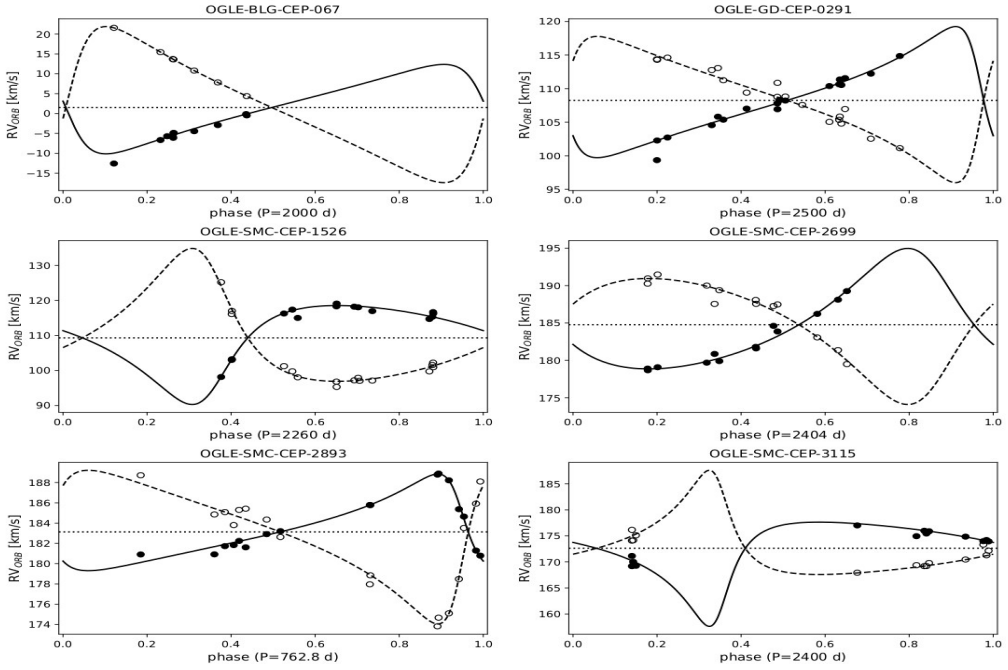


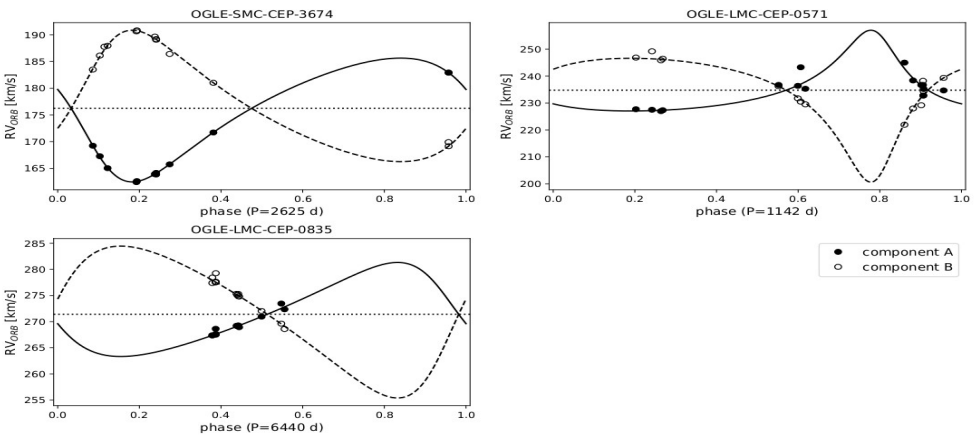




BIND Cepheids

spectroscopic confirmation

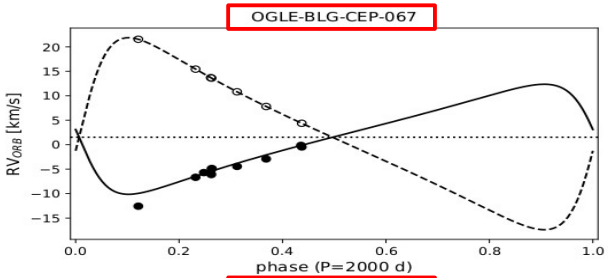


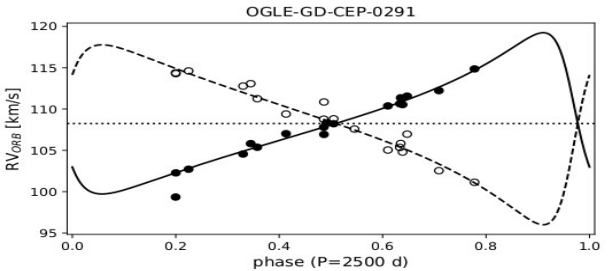


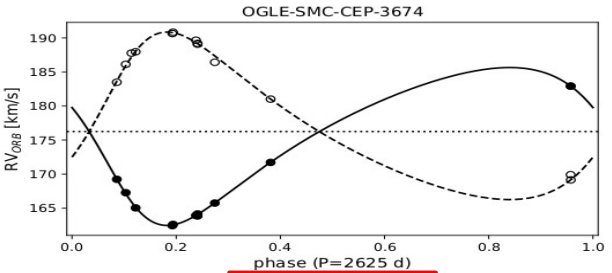
- after disentangling (puls. RV subtracted)
- anticorrelated orbital motion
- spectroscopic confirmation !
- mass ratios...

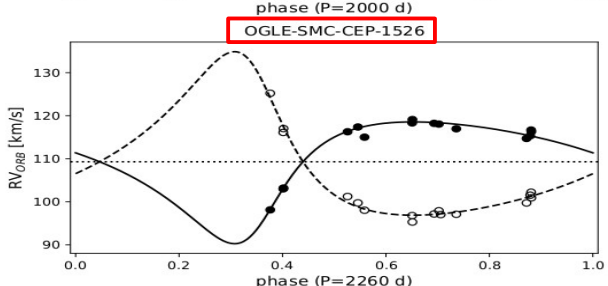
BIND Cepheids

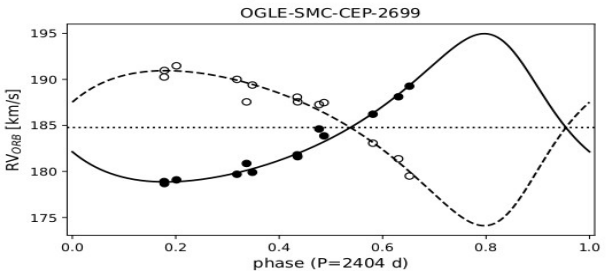
mass ratios

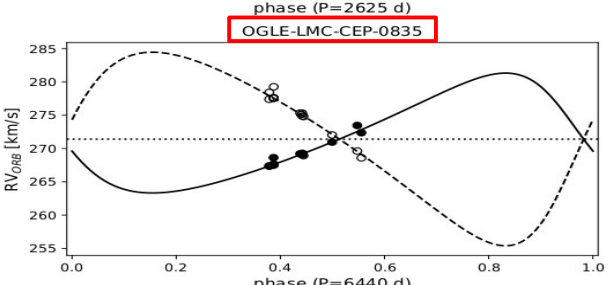


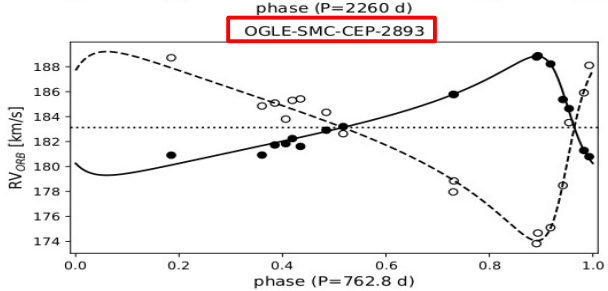


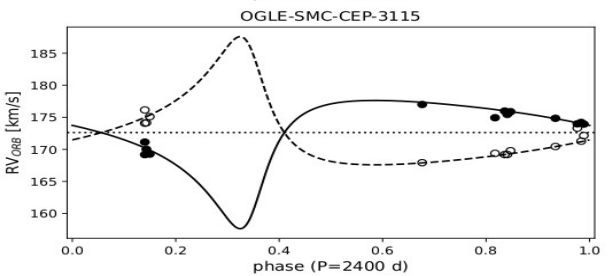


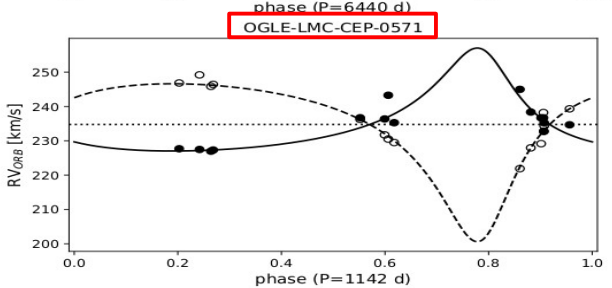






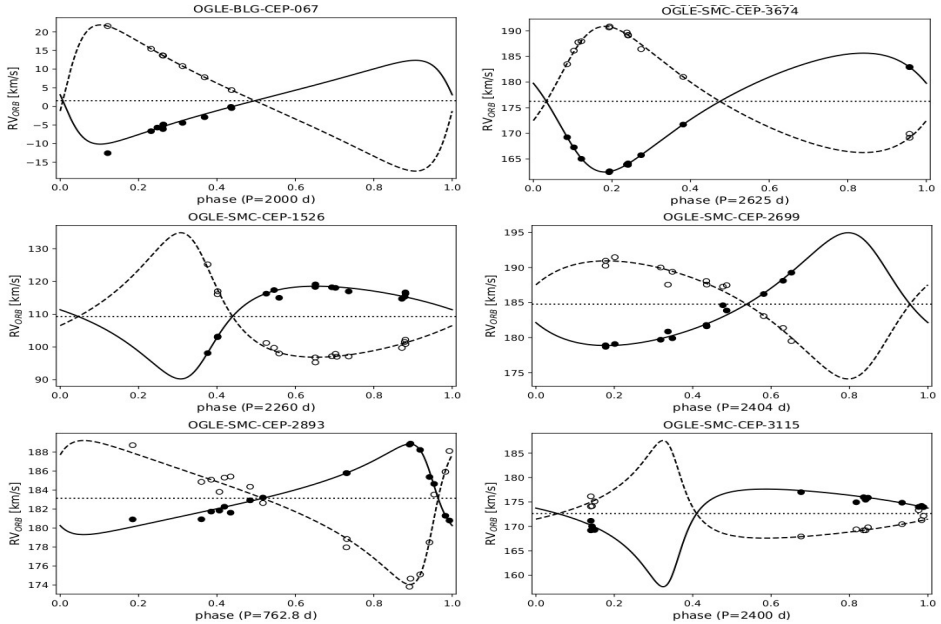






BIND Cepheids

preliminary orbital solutions



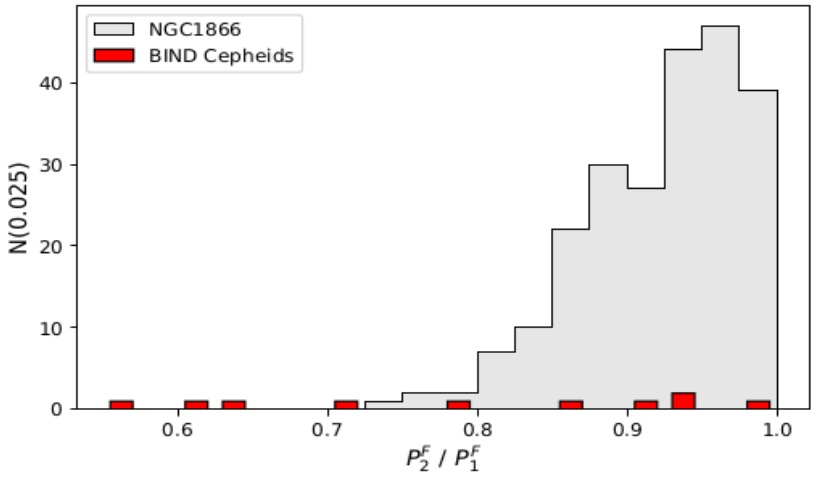
- Preliminary orbital solutions for 3 BIND Cepheids
  - 1526 – high min. masses (high inclination)
  - 2893 – face-on orbit (low P_{orb})
- mass ratios vs. period ratios
- Merger origin of one component
  - Triple --> binary
  - Triple systems common?

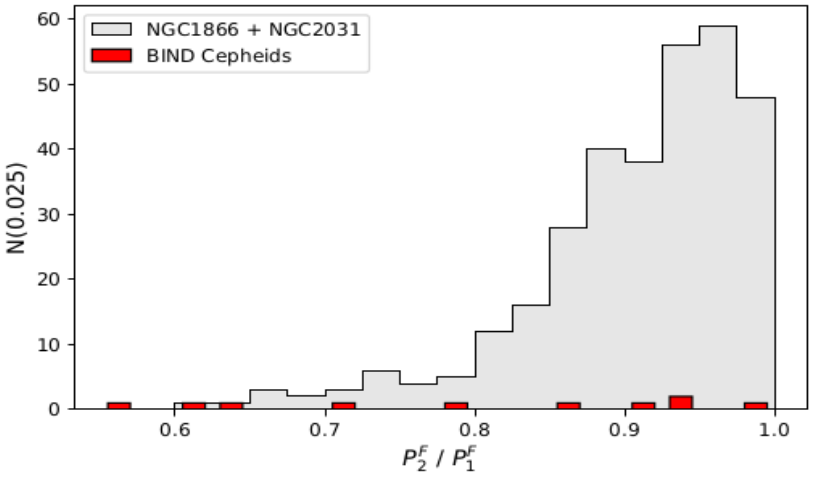
P_2^F/P_1^F
0.639
0.927
0.992
0.603
0.786
0.715
0.561
0.860
0.926
0.920

OGLE ID	T_0 [days]	P_{orb} [days]	q	$M_1 \sin^3(i)$ $[M_\odot]$	$M_2 \sin^3(i)$ $[M_\odot]$	$A \sin(i)$ $[R_\odot]$	e	P_2^F/P_1^F	R_2/R_1
SMC-CEP-1526	8298±12	2260*	0.74±0.09	3.7±0.7	2.8±0.6	1350±90	0.42±0.05	0.715	0.71±0.04
SMC-CEP-2893	9212±6	762±7	0.63±0.06	0.05±0.01	0.03±0.01	150±9	0.58±0.04	0.860	0.74±0.03
SMC-CEP-3674	9256±21	2625*	0.94±0.13	1.7±0.4	1.6±0.3	1190±80	0.31±0.05	0.914	0.92±0.06

BIND Cepheids

period ratios - test





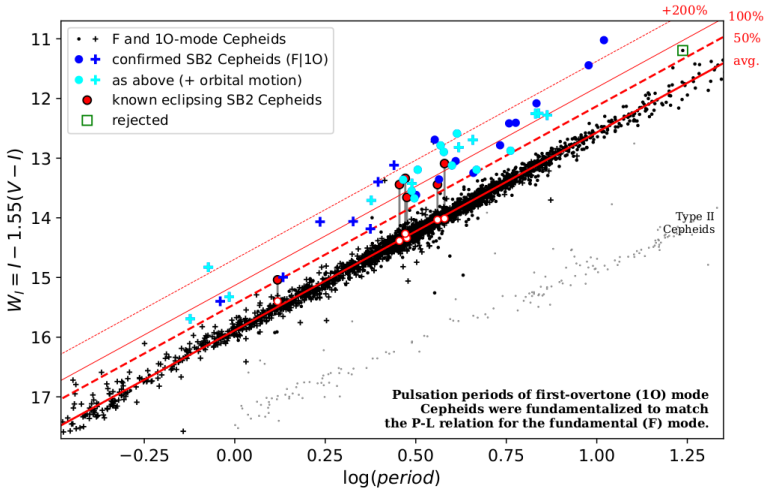
- BIND Cepheids (P_{puls} 1.14-4.56 days); 50% with $P_2/P_1 < 0.8$
- Simulating binaries with ~same-age cluster Cepheids:
  - 22 Cepheids in NGC 1866 (P_{puls} 2.64-3.52 days)
  - 12 Cepheids in NGC 2031 (P_{puls} 2.66-4.43 days)
  - 7% with $P_2/P_1 < 0.8$

P_2^F / P_1^F
0.639
0.927
0.992
0.603
0.786
0.715
0.561
0.860
0.926
0.920

BIND Cepheids

period-luminosity relations

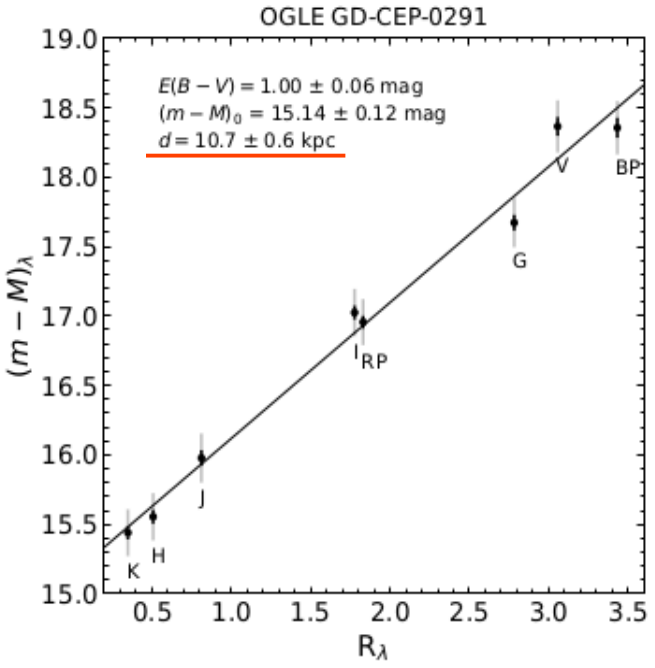
- 80% of Cepheids are in binaries
- Extra light from companions
- => brighter P-L relations (PLRs)
- 8 binary double Cepheids in the LMC/SMC
- Total light can be split between two Cepheids
- On average they lie below their PLRs
  - True Cepheid PLR fainter by:
    ΔW(I,V) = 0.024 +/- 0.010 mag
- First empirical evidence for that!
- Larger sample needed to confirm and increase precision

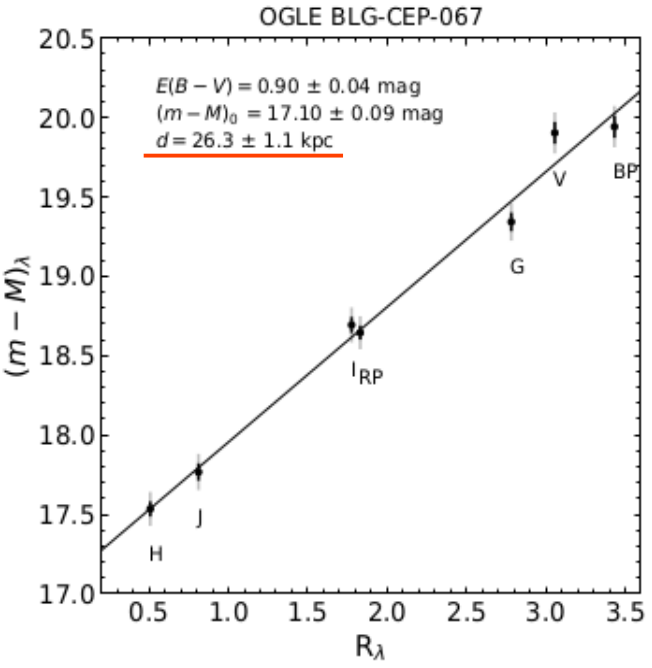


BIND Cepheids
distances

- LMC and SMC objects – known distances
- MW objects
  - modified multi-band method
  - d + E(B-V)
- GD: 10.7 kpc

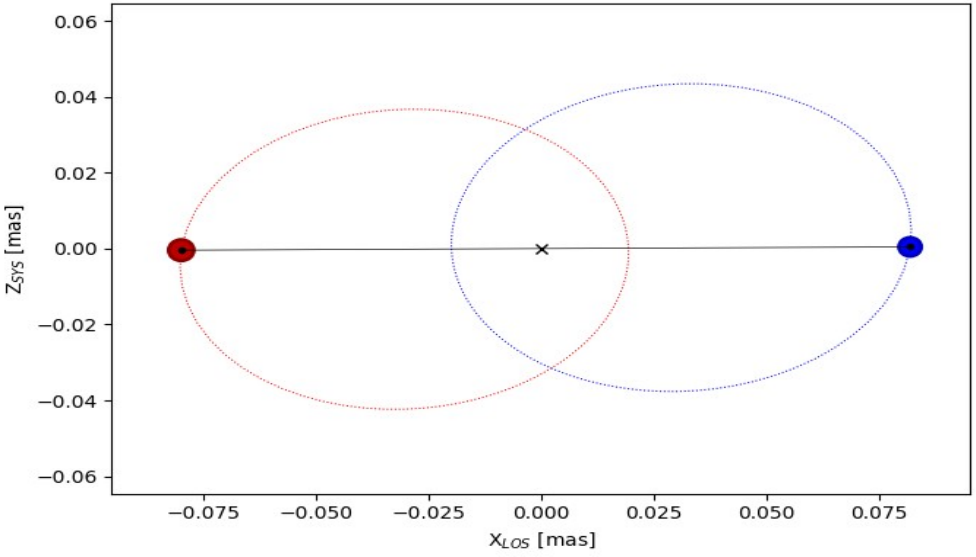
  BLG: 26.3 kpc (beyond GC)
- closest SB2 Cepheids known

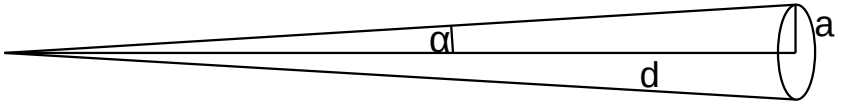




BIND Cepheids
wide orbits

- Previously widest extragalatic:
  4.2 yr / ϕ = 0.16 mas
  (eclipsing binary Cepheid)
- BIND Cepheids
  - long orbital periods
    (up to ~18 years)
- best candidates for direct geometric distance measurements
- GD object: ϕ ~ 1 mas
  (interferometry)
- LMC object (P~18 yr)
  ϕ high but n.y.d.





SB2 single and double Cepheids
summary

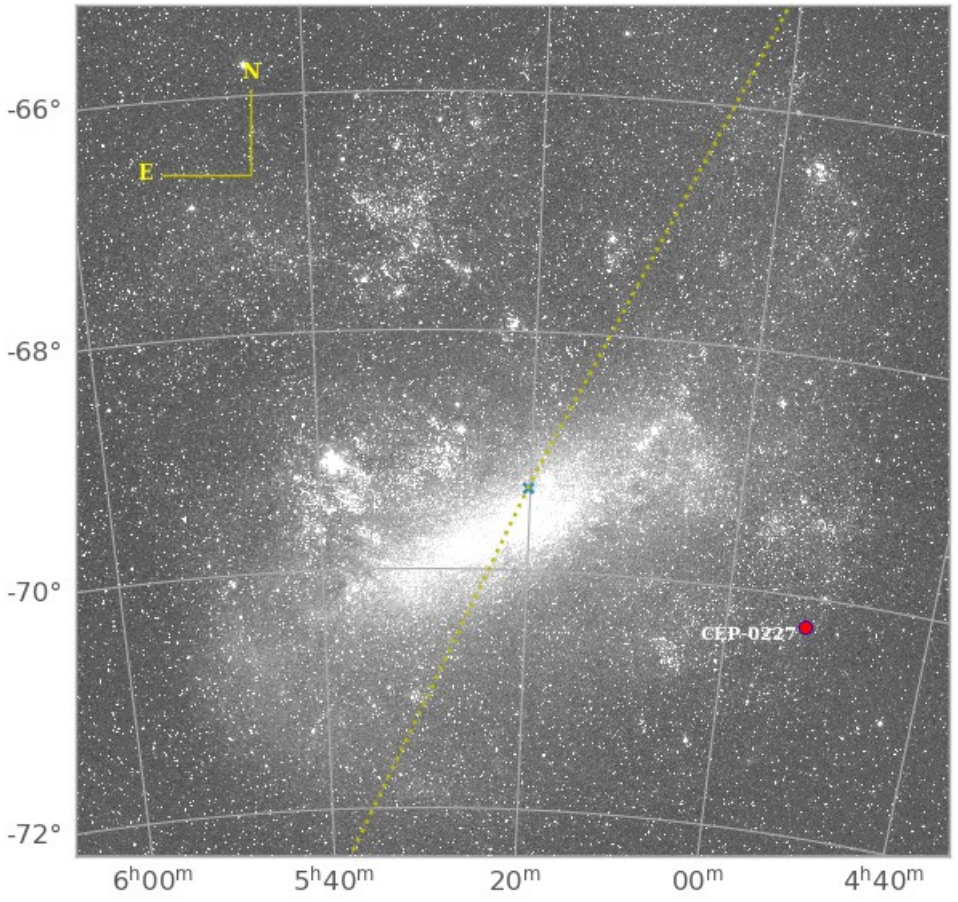
- Explanation of overbright Cepheids
- 60 LMC/SMC/MW Cepheids in SB2 systems (10x more)
  - 9 new binary double (BIND) Cepheids (1 => 10)
- First giant+giant SB2 binary Cepheids in the MW and SMC
- Closest such SB2 Cepheids ~10.7 kpc
- Low period ratios / Low mass ratios
  - => merger origin for a significant fraction of Cepheids
- BIND Cepheids good for testing P-L relations
- Longest-period / highest-separation extragalactic binaries
  - Direct geometric distances (in future)

LMC binary Cepheids

spectroscopically confirmed

in 2010

#: 1

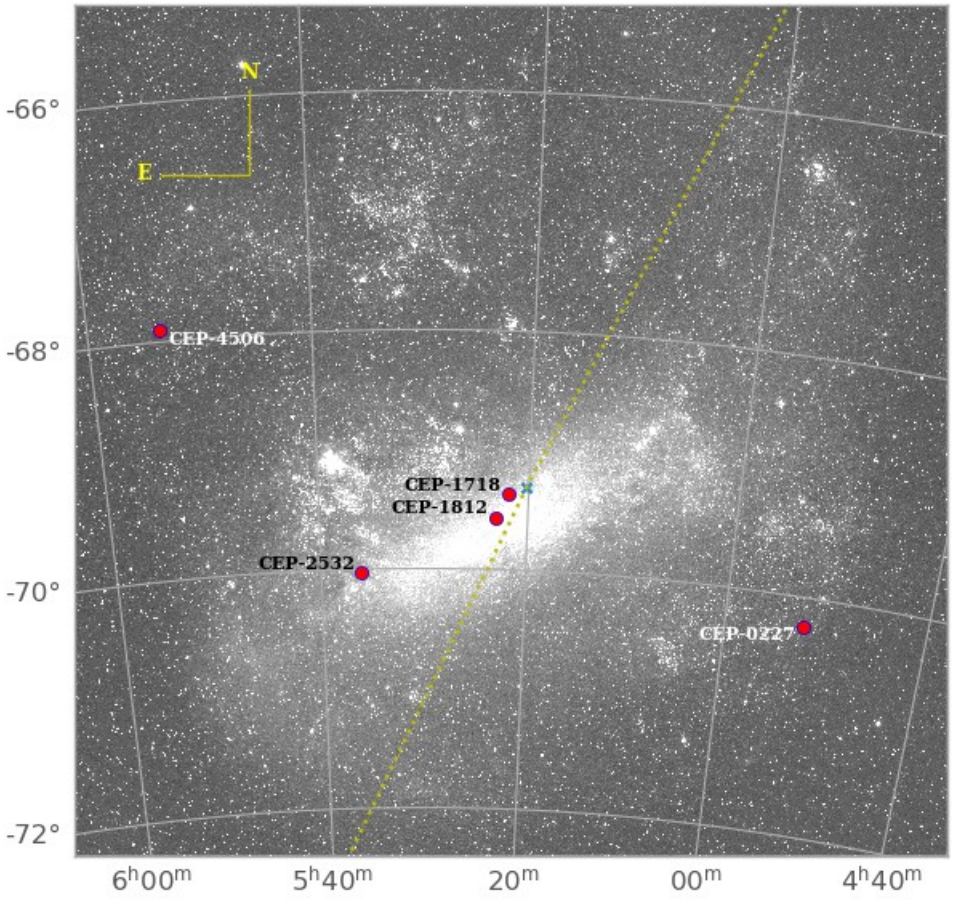


LMC binary Cepheids

spectroscopically confirmed

in 2020

#: 5

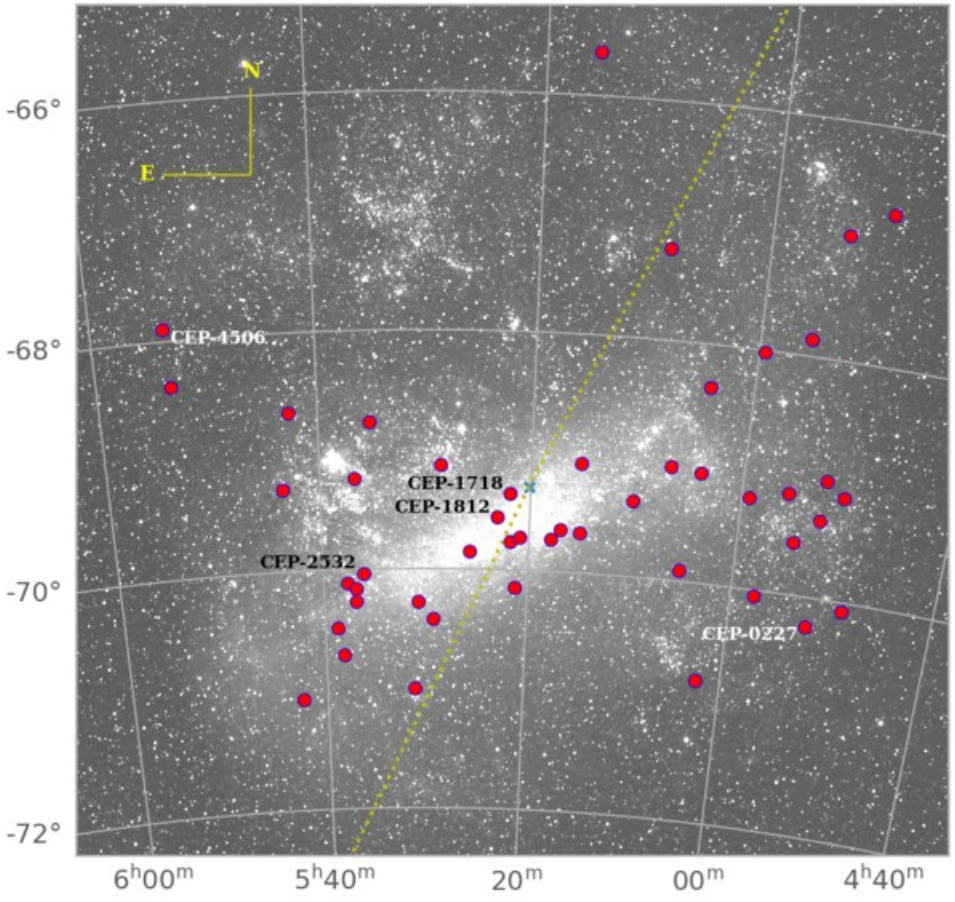


LMC binary Cepheids

spectroscopically confirmed

now

#: ~50



THANK YOU

For references see:
https://users.camk.edu.pl/pilecki/