Discovery of the Longest-Period Classical Cepheid in the Milky Way

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Introduction

- The Optical Gravitational Lensing Experiment(**OGLE**) is a long-term sky survey involving photometric observations of about 2 billion stars in our Galaxy and in the Magellanic Clouds
- **Classical Cepheids** (A.K.A δ Cephei variables or type I Cepheids) are relatively young (< 400 Myr) and luminous (10^2–10^5 $L_\odot$) radially pulsating stars
- The best-known characteristic of Cepheids is the **period–luminosity relation (Leavitt law)** , which is commonly used for measuring intergalactic distances
- Gaia(2023) published radial velocity curves for 9614 stars classified as long period variables (LPVs pulsating red giants)
- OGLE-GD-CEP-1884,**with a period of 78.14 d**, drew their attention due to the distinctive morphology of its light curve.
- **1884** was first identified as a variable star(2015)and categorized as a semi-regular variable(2019)

  (one of the subclasses of LPVs)

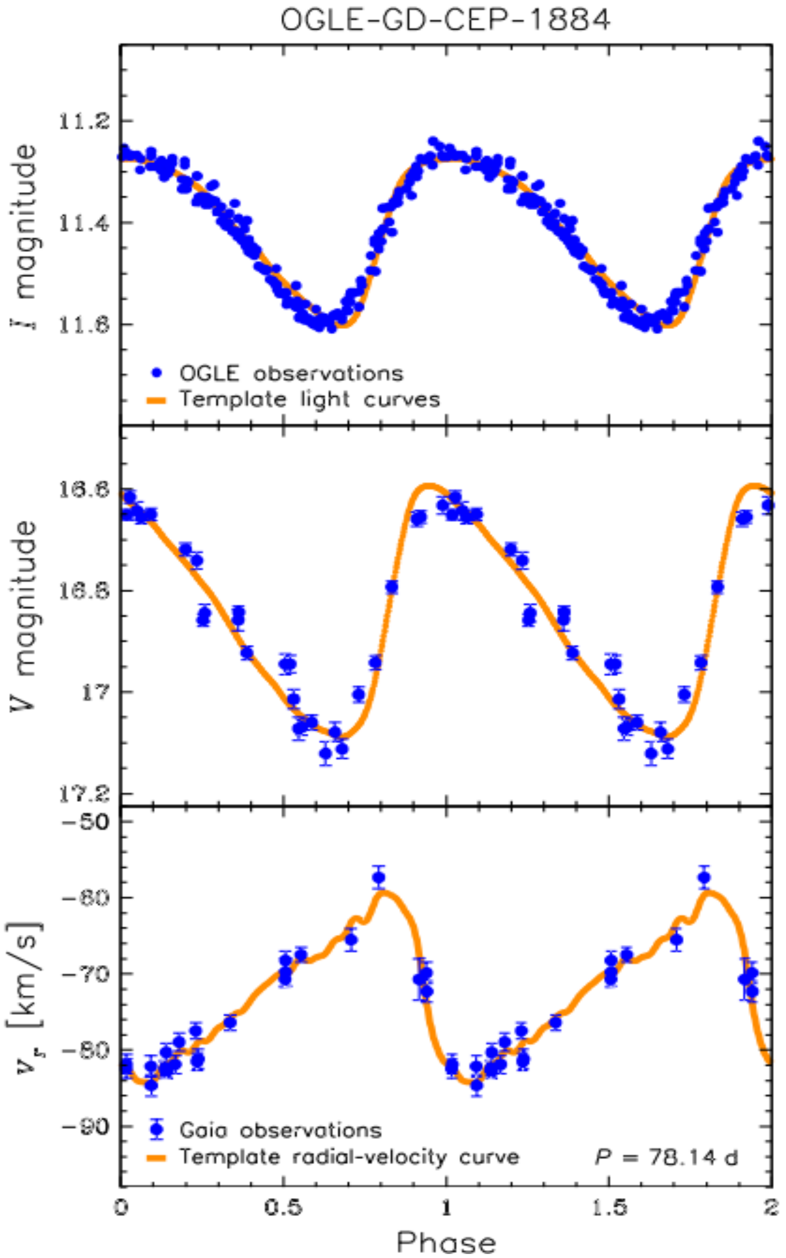
Parameters

Table 1. Parameters of OGLE-GD-CEP-1884

Right ascension [J2000.0]:	15:35:46.70
Declination [J2000.0]:	−55:56:56.4
Galactic longitude [°]:	324.522733
Galactic latitude [°]:	−0.125534
Pulsation period [d]:	78.140 ± 0.011
Mean V-band magnitude (OGLE):	16.83
Mean I-band magnitude (OGLE):	11.40
Mean G-band magnitude (*Gaia*):	12.84
Mean J-band magnitude (2MASS):	7.47
Mean H-band magnitude (2MASS):	6.14
Mean K_S-band magnitude (2MASS):	5.51
Parallax (*Gaia*) [mas]:	0.176 ± 0.077
Proper motion (*Gaia*) [mas/yr]:	5.88 ± 0.08
Mean radial velocity (*Gaia*) [km/s]:	-72.3 ± 0.4
Velocity component U [km/s]:	-9.9 ± 8.5
Velocity component V [km/s]:	220.8 ± 3.9
Velocity component W [km/s]:	-3.4 ± 1.8

The VI-band observations of OGLE-GD-CEP-1884 were obtained as part of the OGLE-IV survey

Classification



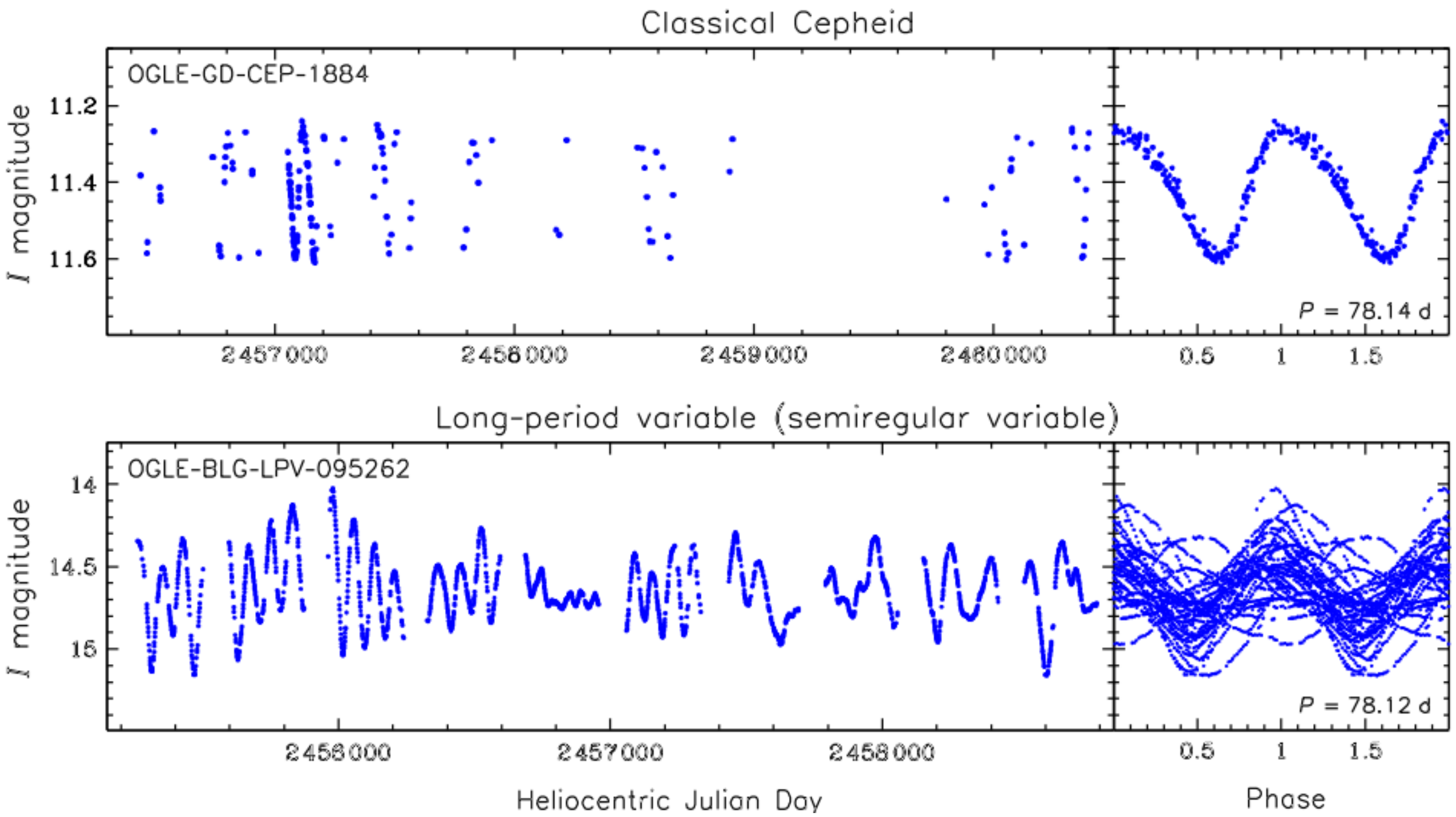
The upper and middle panels of Figure are the I and V-band light curves of OGLE-GD-CEP-1884

After a decade of OGLE photometric monitoring,the period,amplitudes, and shapes of the light curves have remained stable,only slight fluctuations (up to ±0.04 mag in the I band) in average brightness.

The orange curves is the template light and radial velocity curves of a **classical Cepheid** with a period of 78.14 d generated using the code provided by
Pejcha & Kochanek(2012).doi:10.1088/0004-637X/748/2/107

Small differences between the templates and observations (＜0.05 mag) may arise from the **different metallicity** of our star compared to that assumed in the mode(Pejcha.2012)or **minor deviations** of the OGLE-IV filters from the standard filters

Classification



lower panel: light curve of a semiregular variable from the OGLE collection of LPVs in the Galactic bulge

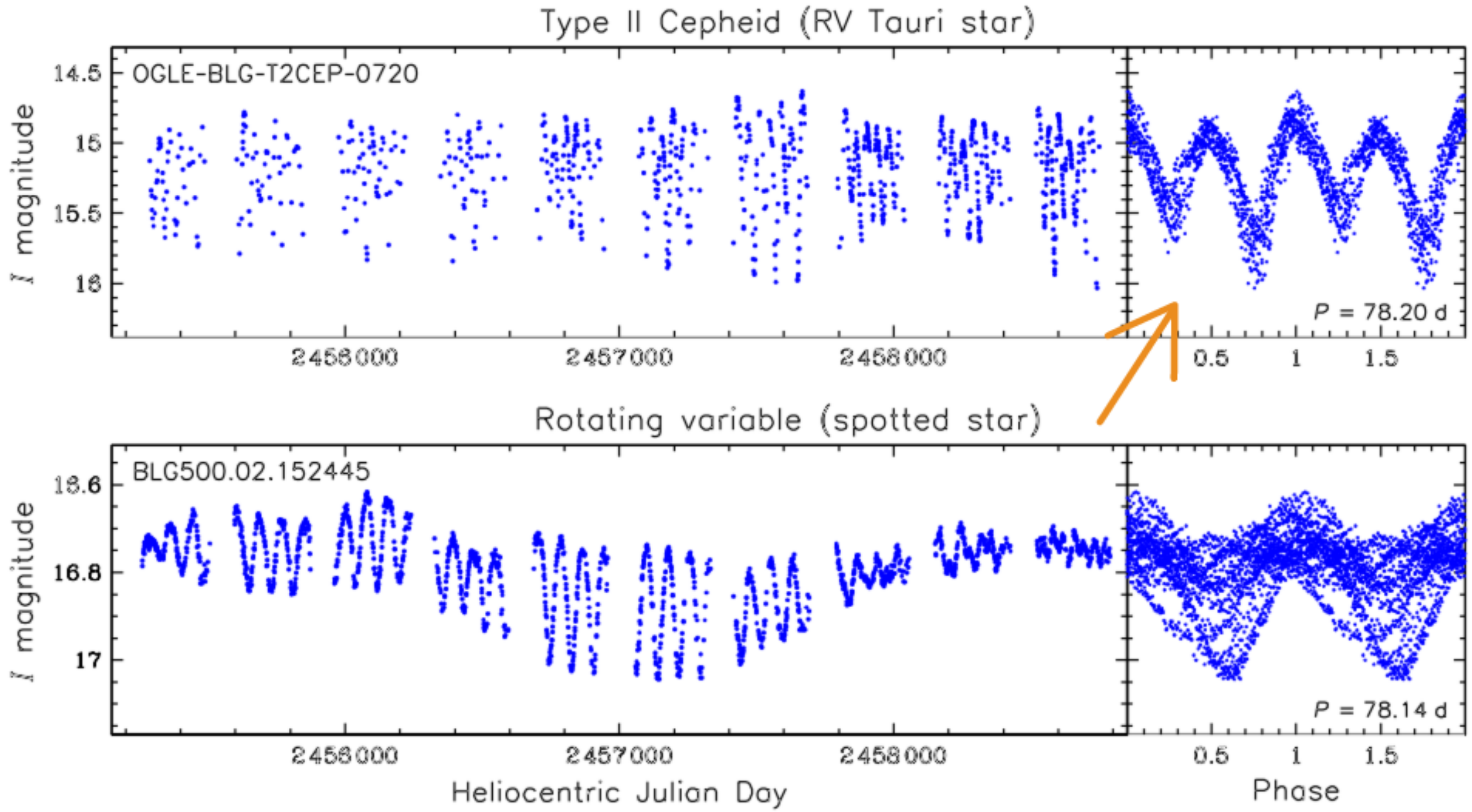
As the name suggests,semiregular variations show significant phase and amplitude fluctuations, quite different from what can be seen in the light curve of 1884.

even the photometric residuals of our target exhibit some dispersion of points, this light curve is far more stable than what is observed in any LPV with the pulsation period of around 80 d.

1884 cannot be classified as a Mira variable(Miras' light curves have amplitudes above 0.8 mag in the I band and 2.5 mag in the V band)

*Mira variables are typically classified as semi-regular variables.

Classification

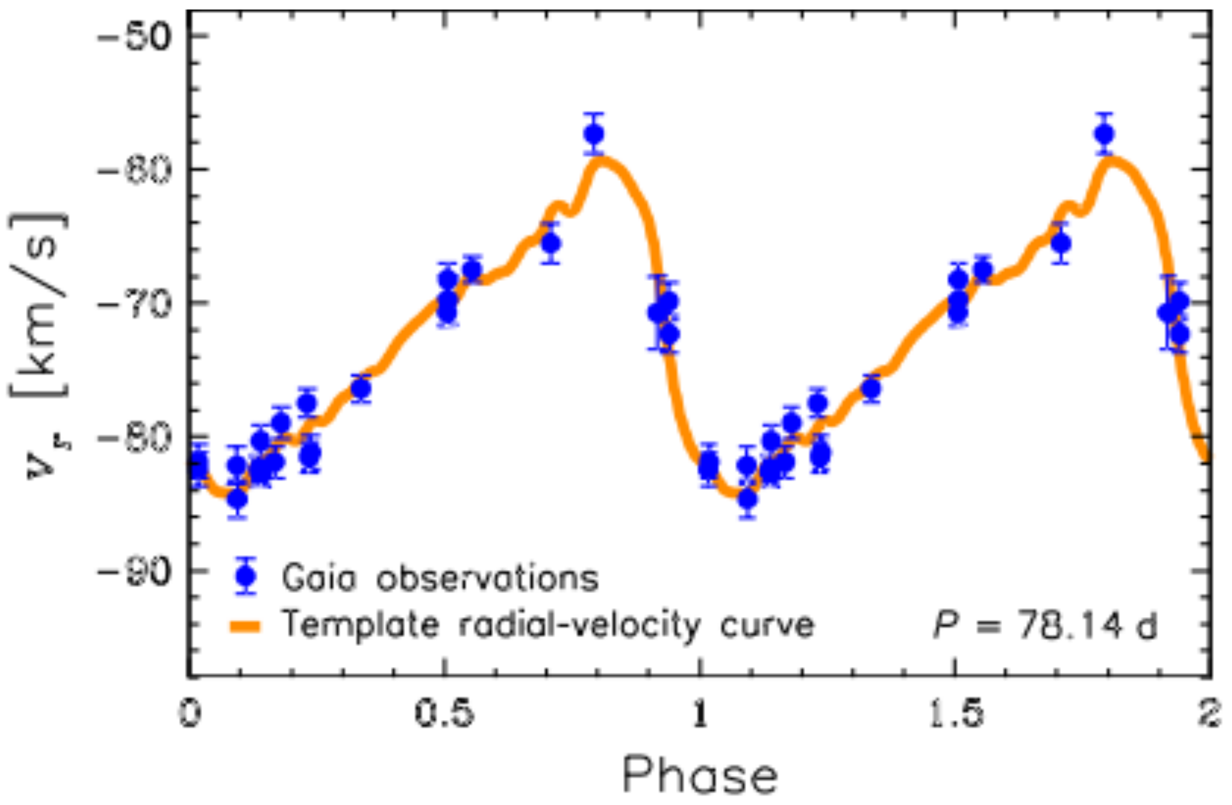


A distinctive feature of this type of variable stars is the alternating **deeper and shallower** minima of the light curve.Moreover,light curves of RV Tauri stars usually exhibit **larger amplitudes** and show **significant variability** from cycle to cycle.

light curves of spotted stars continuously **change their shape** as the spot move on the stellar surface.

upper panel: present a typical time-series photometry of an RV Tauri star
lower panel: present a time-series photometry of typical spotted variable

Classification



radial-velocity curve
published by Gaia Collaboration et al. (2023).

another confirmation

characteristic triangular shape of its radial-velocity curve
[Classical Cepheids typically exhibit a periodic variation in their radial velocities accompanying the changes in their luminosity, forming a characteristic triangular-shaped radial velocity curve.]

Distance

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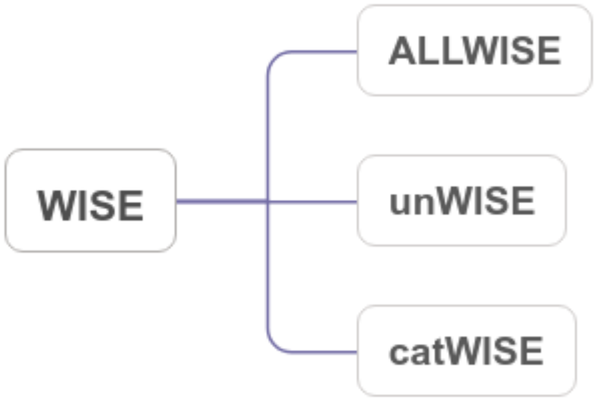
To directly determine the absolute magnitude of this object, knowledge of its distance is necessary.

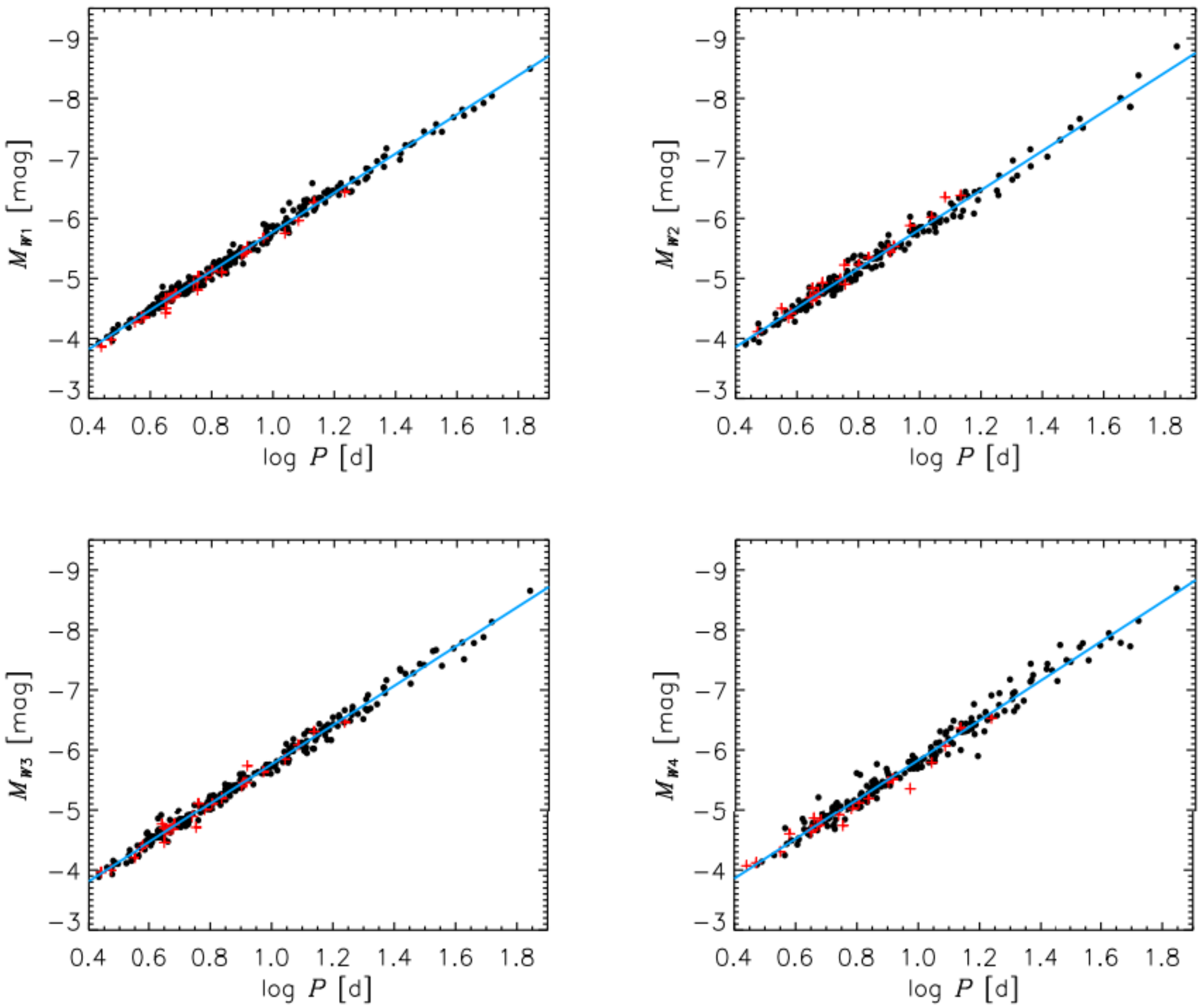
parallax of OGLE-GD-CEP-1884 has a relative uncertainty exceeding 40%(leading to significant uncertainty in the distance)
distance to OGLE-GD-CEP-1884 falls within the range of **3640–5712 pc** (68% confidence interval), with a median value of **4646 pc**.

Distance

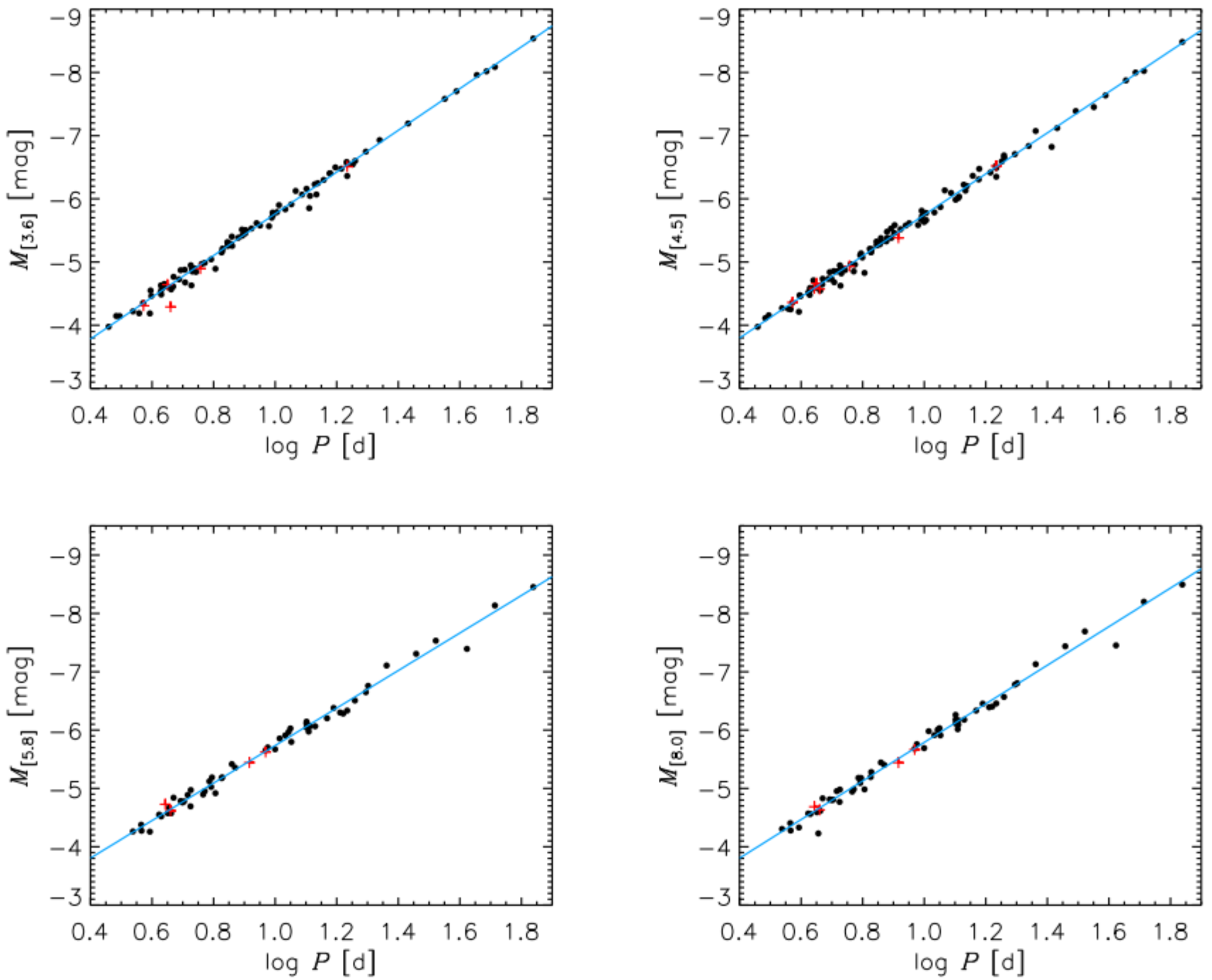
- In order to minimize the effect of interstellar extinction, they utilized **mid-infrared (mid IR) observations** of OGLE-GD-CEP-1884 and **mid-IR period–luminosity relations** rather than the optical ones,to calculate the Cepheid distance.
- OGLE-GD-CEP-1884 has been observed in the mid IR by the Wide-field Infrared Survey Explorer(WISE)in the W_1 [3.4 μm], W_2[4.6 μm], W_3 [12 μm], and W_4 [22 μm] bands
- The Cepheid has also been observed by the **SpitzerSpace Telescope** in the I_1 [3.6 μm],I_2 [4.5 μm], **I_3 [5.8 μm] and I_4 [8.0 μm]** bands



- $M = a_\lambda \log P + b_\lambda$ (fundamental mode classical Cepheids)
- the best-fitting results for the mid-IR WISE and Spitzer PL relations



WISE bands



Spitzer bands

Band (λ)	N	a_λ	b_λ	σ
All Cepheids				
$W1$	282	-3.258 ± 0.018	-2.519 ± 0.017	0.082
$W2$	212	-3.266 ± 0.027	-2.551 ± 0.026	0.108
$W3$	286	-3.270 ± 0.019	-2.505 ± 0.019	0.090
$W4$	219	-3.315 ± 0.030	-2.530 ± 0.031	0.123
[3.6]	90	-3.302 ± 0.023	-2.461 ± 0.023	0.066
[4.5]	106	-3.246 ± 0.023	-2.499 ± 0.023	0.071
[5.8]	59	-3.216 ± 0.042	-2.519 ± 0.043	0.097
[8.0]	59	-3.307 ± 0.040	-2.482 ± 0.041	0.091
Excluding First-Overtone Cepheids				
$W1$	255	-3.248 ± 0.018	-2.533 ± 0.018	0.082
$W2$	190	-3.266 ± 0.027	-2.545 ± 0.027	0.107
$W3$	258	-3.263 ± 0.020	-2.512 ± 0.020	0.090
$W4$	197	-3.317 ± 0.032	-2.534 ± 0.033	0.125
[3.6]	85	-3.298 ± 0.024	-2.467 ± 0.024	0.066
[4.5]	99	-3.245 ± 0.024	-2.502 ± 0.024	0.073
[5.8]	55	-3.222 ± 0.044	-2.511 ± 0.045	0.099
[8.0]	55	-3.311 ± 0.042	-2.479 ± 0.044	0.093

Parameters of the Galactic mid-IR PL Relations

Wang, S., Chen, X., de Grijs, R., & Deng, L. 2018, ApJ,852, 78. doi:10.3847/1538-4357/aa9d99

Distance

- Even the extinction is small at the mid-IR wavelengths, it is still non negligible within the Galactic plane, therefore they used the **mwdust 3D extinction maps** that provide extinction values in the K_S band for a given on-sky location and distance
- The extinction value extracted from mwdust is $A_{KS} \approx 0.84$ mag, and after transforming to mid-IR
  $A_{W1} \approx 0.47$, $A_{W2} \approx 0.40$, $A_{W3} \approx 0.43$, $A_{W4} \approx 0.34$,
  $A_{I1} \approx 0.40$, and $A_{I2} \approx 0.39$ mag

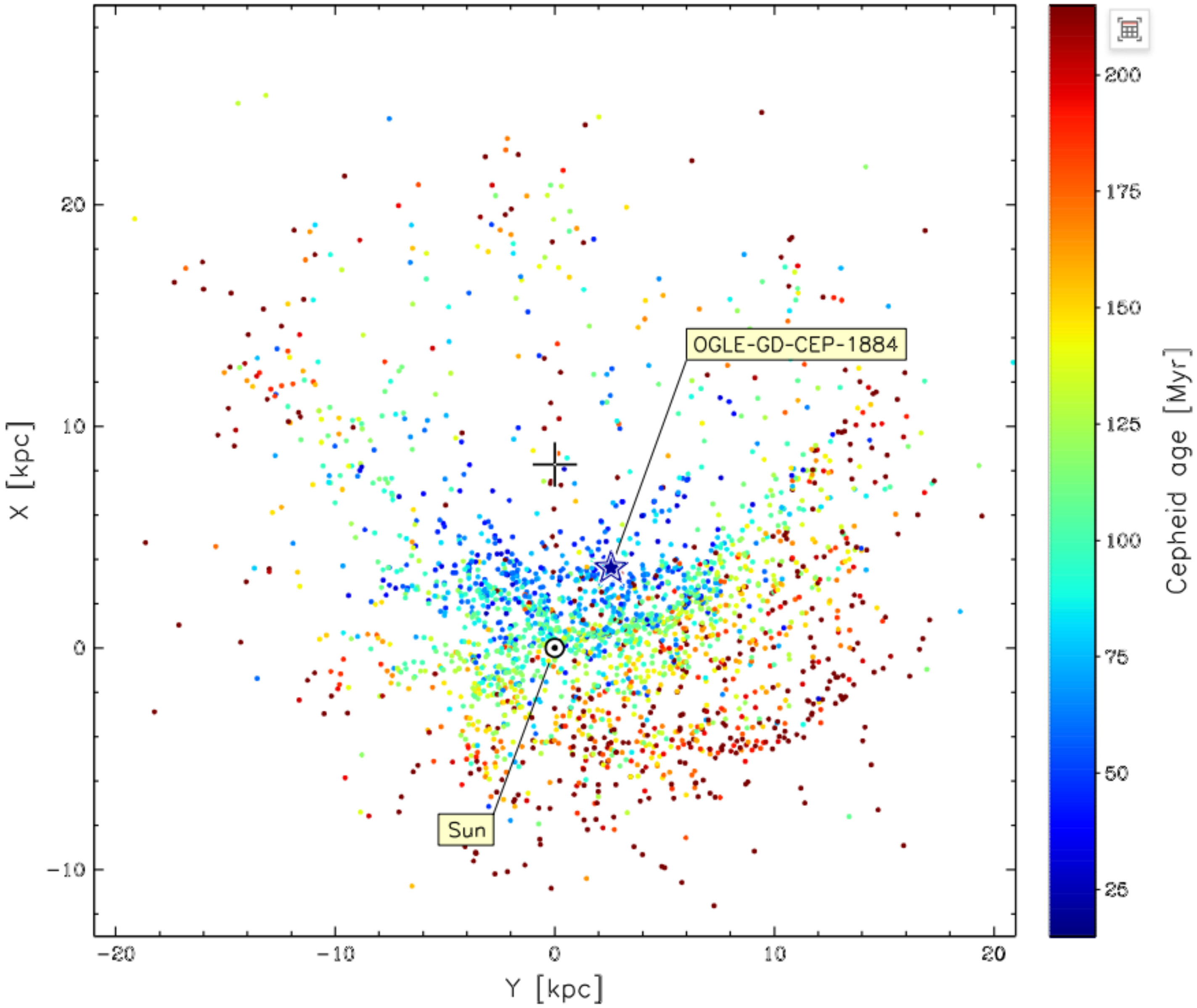
Distance

Table 2. Mid-IR magnitudes and distances of OGLE-GD-CEP-1884

Catalog	W1 [mag]	d_{W1} [pc]	W2 [mag]	d_{W2} [pc]	W3 [mag]	d_{W3} [pc]	W4 [mag]	d_{W4} [pc]	I3 [mag]	d_{I3} [pc]	I4 [mag]	d_{I4} [pc]
AllWISE	4.96	4319	4.90	4417	4.98	4461	4.68	4275	–	–	–	–
unWISE	5.36	5121	4.96	4543	–	–	–	–	–	–	–	–
CatWISE	5.38	5161	4.72	4092	–	–	–	–	–	–	–	–
Spitzer GLIMPSE	–	–	–	–	–	–	–	–	4.99	4483	4.91	4741

The **saturation limits** for WISE: W_1(8 mag) ,for W_2(7mag),W_3(3.8mag) and W_4(-0.4 mag)
D(mid-IR period–luminosity relations)= 4472 pc(σ = 166 pc)
D(parallax)= 4646pc

Distance

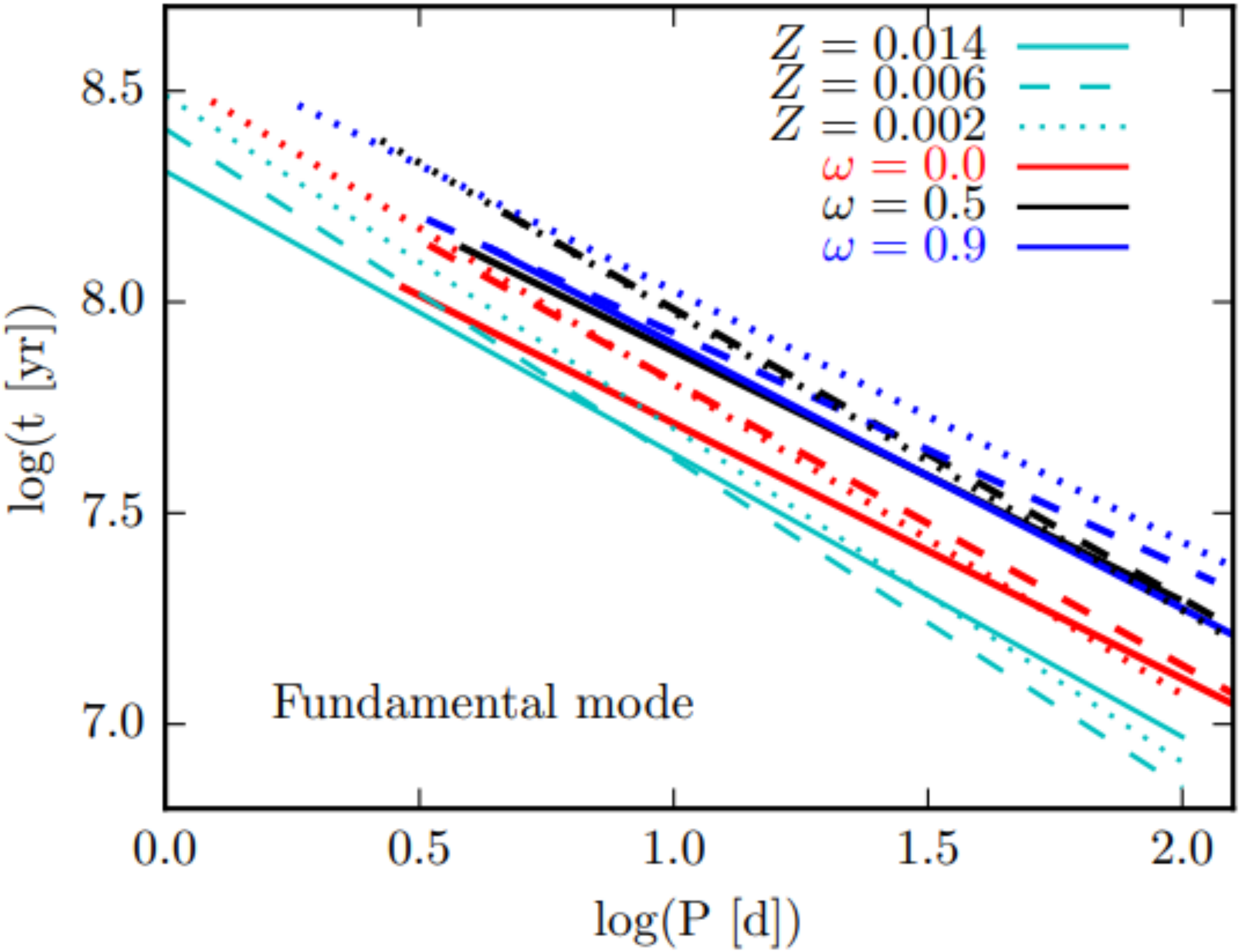


Points are colorcoded according to the Cepheid ages, estimated using the **period–age relations** derived by Anderson et al.(2016).

①**initial rotation** of ω = 0.5
②an unknown **crossing number** and **location** of our Cepheid within the instability strip
③took into account the **metallicity** gradient in our Galaxy reported by Genovali et al. (2014).
The resulting age of OGLEGD-CEP-1884 is **22 Myr**

why

- Longer-period Cepheids tend to have higher initial masses,and hence tend to be younger than Cepheids of shorter periods.
- Rotation affects period-age relations **via** mixing processes that supply the core with fresh material which is particularly important during hydrogen burning on the MS
- rotation affects MS lifetimes monotonously: **the faster the initial rotation of a model with fixed mass, the longer its MS lifetime**.At the time when a star of a given mass finally crosses the IS,its age as a Cepheid depends on its MS lifetime
- the rotating models to yield a **higher age** than the nonrotating models for a given luminosity and thus, period
- Crossing number(number of crossings through the instability strip):3rd crossing Cepheids are older than those on a second crossing



Period age relations as function of different **initial rotation rate** and **metallicity**, averaged over 2nd and 3rd crossing and the width of the instability strip.

the **effect of rotation** on the period-age relation is **similar to or greater** than the effect of metallicity.

		Fundamental Modes						First Overtones					
Z	Xing	α_b	β_b	α_r	β_r	α	β	α_b	β_b	α_r	β_r	α	β
		FU Blue Edge		FU Red Edge		FU IS avg		1O Blue Edge		1O Red Edge		1O IS avg	
0.014	2nd	-0.702	8.481	-0.573	8.527	-0.532	8.393	–	–	-0.764	8.538	-0.713	8.432
	3rd	-0.692	8.520	-0.599	8.623	-0.641	8.551	–	–	-0.778	8.65	-0.666	8.475
0.006	2nd	-0.675	8.444	-0.696	8.727	-0.706	8.654	-0.695	8.346	-0.793	8.665	-0.823	8.622
	3rd	-0.656	8.497	-0.620	8.685	-0.671	8.653	-0.671	8.394	-0.804	8.713	-0.840	8.694
0.002	2nd	-0.896	8.610	-0.916	8.844	-0.827	-0.859	8.706	8.41	-1.166	8.873	-1.065	8.726
	3rd	-0.833	8.793	-0.784	8.960	-0.803	8.869	-0.892	8.694	-0.798	8.803	-0.839	8.763
						FU Xing avg						1O Xing avg	
0.014	avg					-0.592	8.476					-0.633	8.406
0.006	avg					-0.665	8.628					-0.825	8.651
0.002	avg					-0.840	8.794					-0.961	8.768

Period-age relations **($\log t = \alpha \cdot \log P + \beta$)** for $\omega = 0.5$(average rotation)

Cepheid ages are uncertain to 50% if crossing numbers, IS position, and,importantly, the rotational histories are not known

OGLE-GD-CEP-1884 as an Ultra Long Period Cepheid

- ultra long period (ULP) Cepheids(P~80d*relaxed definition)
- To date, not a single ULP Cepheid has been identified in the Milky Way .However 72 ULP Cepheids have been identified within 26 neighboring galaxies
- The discovery of OGLE-GD-CEP-1884 suggests that ULP Cepheids are also present in our Galaxy, probably in the regions strongly affected by interstellar extinction

Conclusion

- They reported the discovery of the longest-period classical Cepheid known in the Galaxy. Its pulsation period,78.14 d
- It can be utilized for improving the fitting of the Leavitt law,investigating the youngest structures of the Galaxy, and studying the evolution of massive stars.
- This suggests that there might be more such long-period classical Cepheids in the Galaxy that remain undetected, and the Milky Way does not differ in the number of long-period Cepheids compared to other galaxies.
- The fact that this star was misclassified as an LPV indicates the need for improvement of algorithms for automated classification of variable stars.