*Astronomy & Astrophysics* manuscript no. output
July 4, 2019
© ESO 2019

# Proyect Group 1 - Variable Stars

Giannina Boggiano[1], Carolina Cenzano[1], Constanza Muñoz[1], and Álvaro Valenzuela[1,2]

[1] Instituto de Astrofísica, Pontificia Universidad Católica de Chile, Av. Vicuña Mackenna 4860, 782-0436 Macul, Santiago, Chile
e-mail: cmcenzano@uc.cl
[2] Millennium Institute of Astrophysics, Santiago, Chile

Received July 4, 2019; accepted July 9, 2019

**ABSTRACT**

*Aims.* Search Classical Cepheids in different databases and calculate the periods for different segments of the resulting light curve.
*Methods.* From the surveys OGLE, EROS, DASCH and MACHO it was downloaded the photometry of the Classical Cepheids with their mode of pulsation in the fundamental mode. In this case, OGLE was the survey with the most reliable variable classification, so from the surveys EROS, DASCH and MACHO were selected the cepheids that were also in OGLE catalog by doing crossmatch. Then, in other to create a common lightcurve, a normalization was made to all the data by choosing an amplitude of a star and moving every mean magnitude to zero.
*Results.* The final data contains 2435 Cepheids, with 1152 stars from MACHO in b and r, 412 stars from EROS in B and R, and 373 stars from DASCH. Only 53 contains data of OGLE, DASCH and EROS, 152 from OGLE, DASCH and MACHO and finally 100 from OGLE, EROS and MACHO. The results are concentrated first between the years 2001-2015 (OGLE), second between 1900-2000 (OGLE, EROS and MACHO) and then between 1921 and 1954 (DASCH).

**Key words.** Stars: variables: Cepheids – Galaxy: Large Magellanic Cloud: Surveys – Catalogs

## 1. Introduction

Cepheids are massive stars of between four and twenty solar masses, with very regular periods that are usually from a few hours to months, whose magnitudes vary between hundredths and up to 2 units. Unlike non-radial variables, they retain their spherical shape during pulsation. It has been proven that the spectral type is more advanced than the period. The spectral type in the maximum is F, and in the minimum they can oscillate between G and K. Of all the characteristics that these stars present, the most important is the relation that exists between their period and their luminosity. These stars are relatively young in the burning phase of He and occupy space in a band of well-defined instability in the H-R diagram. These are considered an excellent marker to understand the recent formation of stars in the host galaxy and one of the most important establishments of the cosmic distance scale (Joshi & Panchal 2019). They are easily detectable due to their high intrinsic brightness. on the outskirts of the galactic disk and in nearby galaxies like the LMC.

The Cepheids in the Magellanic Clouds have played an important role in the scale of distance and the determination of the present value of the expansion rate of the Universe, the Hubble constant ($H_0$). With the knowledge of the distance to the Large Magellanic Cloud (LMC), we can directly determine the absolute magnitudes of these pulsating stars (Riess & Scolnic 2019).The LMC is located in one of the most studied galaxies in the Universe due to its proximity to the Galaxy, which is at a distance of 50 kpc.

In this project we will focus on the Large Magellanic Cloud (LMC) in order to determine the variation rates in the period of classic Cepheid type variables, comparing the results with the expected values according to stellar evolution and pulsation theories.

Particularly in this part of the project we show how we obtained the data from the different databases, in this case: OGLE, EROS, MACHO and DASH, obtaining the corresponding light curves, also making the time measurements consistent from a case to other. On the other hand, we calculate the periods for different segments of the resulting light curve, visualizing if there could be significant changes in the periods of each star or not.

## 2. The Data

For this project, it was used the data of four surveys: OGLE, MACHO, EROS and DASCH.In this project it was only used Classical Cepheids with fundamental pulsation mode.

### 2.1. OGLE

The Optical Gravitational Lensing Experiment (OGLE)[1] is a Polish astronomical project based at the University of Warsaw, since 1992 until nowadays. The main objective of these project is to detect and classification of variable stars in the Magellanic Clouds and the Galactic Bulge. Most of the observations have been made at the Las Campanas Observatory in Chile, with the 1.3 m Warsaw telescope.

[1] http://ogle.astrouw.edu.pl/

The project has 4 phases, and fortunately for our project, all the data is public access [2].

The first one was OGLE I (1992-1995), but this was not consider in this investigation because it only target the bulge and some globular clusters.

OGLE II (19962000) had their data separated by field as it can be seen in Figure 1, so each folder was download individually. There were 722 fundamental mode cepheids in this data release, but their mode of pulsation and period where not establish until OGLE-III.

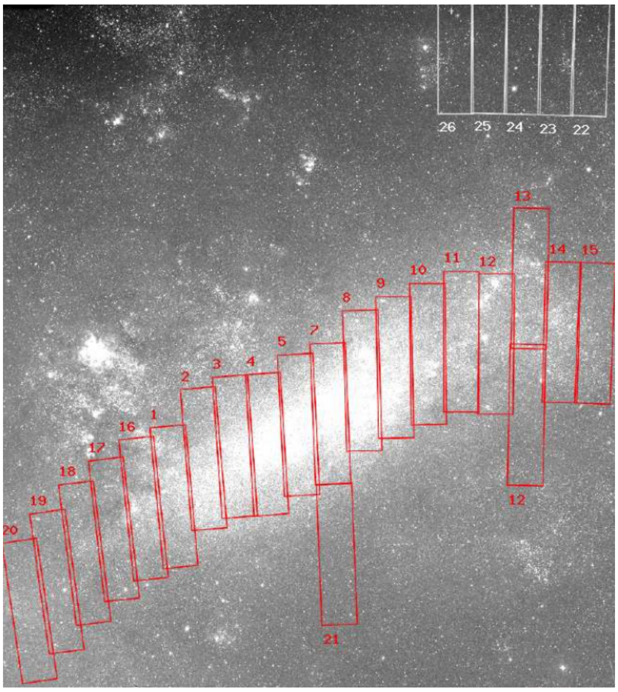


**Fig. 1.** OGLE-II fields in the LMC.

For OGLE III (20012009) and OGLE-IV (2010-) the data was divided by their unique id, which include the target zone, their variability type and their number SoszyÅski et al. (2008). They count with their photometry in the bands V and I with the information of the epoch in HJD (HJD-2450000.0), their magnitude and the error associated. Their mode of pulsation, ID in OGLE II, ID in the GCVS was included in a file called " ident.dat ", while their information about their period(s) and fourier decomposition were included in a separated file that dependent in their mode of pulsation. As we are only using fundamental mode cepheids (CEPF), so the file with their period information is called " cepF.dat ".

In OGLE-III there are 1849 CEPF, and in OGLE-IV 2474 CEPF. The data of OGLE-III and OGLE-IV is very similar, with the difference that in OGLE-IV there were found 637 new CEPF that in the previous release, and of course more photometry data for almost all the 1849 CEPF remainder.

The process to combine OGLE-II (different ID) with OGLE-III and OGLE-IV was to made a crossmatch by name following the " ident.dat ", because it has the id from OGLE-II.

However, not all the stars in the " ident.dat " make it to the final data. Actually, there were some cepheids that were only available in OGLE-III and did not have their photometry in OGLE-IV. This was the case, for example, of OGLE-LMC-0712, that was likely to be saturated in OGLE-IV, as it can be seen in Figure **??**. In this cases, all the cepheids that where not present in OGLE-IV were discarded, even if they were in previous versions, to prevent errors in their photometry.

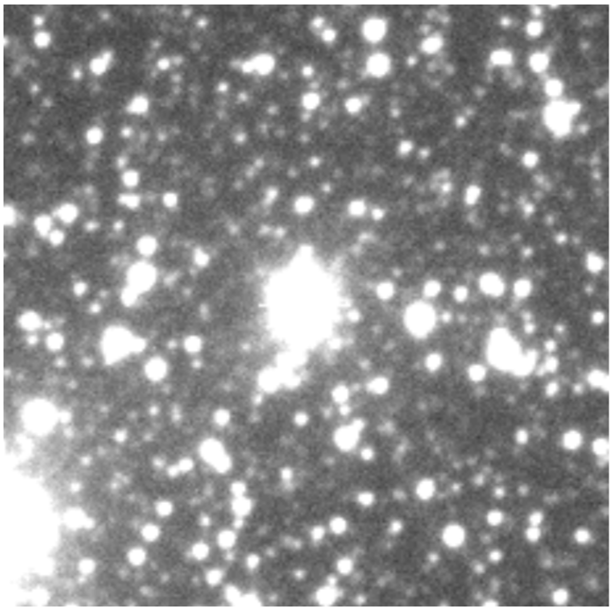

**Fig. 2.** OGLE-LMC-0712 in OGLE-IV

Also, in other to make sure that we were analysing fundamental mode cepheids, their lightcurves were plotted with the period from ident.dat. In this file it could be seen that some light curves does not correspond to the shape of a Classical Cepheid in their fundamental mode, like OGLE-LMC-0016, as it can be seen in the Figure 3, However, as it still necessary to do a crossmatch with data from others surveys, this could change and it could be found a better period, because maybe this star correspond to a Cepheid and the period is badly measured, it cannot be tale only with this information.

Since OGLE is the survey with the most confident variable classification from all four surveys, the recollection of data from the MACHO, EROS and DASCH was based in the 2474 classical cepheids from OGLE-IV.

### *2.2. EROS*

EROS stands for 'Exprience pour la Recherche d'Objets Sombres' and has known 2 observational phases : EROS-1 (1990-1995) and EROS-2 (1996-2003)[3] . EROS-2 monitored the LMC/SMC, the Galactic center, and the spiral arms during its operation from July 1996 to March 2003 using the 1m Ritchey-Chretien telescope, MARLY, at ESO (La Silla, Chile). The telescope was equipped with two cameras, one observing in

[2] OGLE data Online: `http://www.astrouw.edu.pl/ogle/`

[3] `http://eros.in2p3.fr`

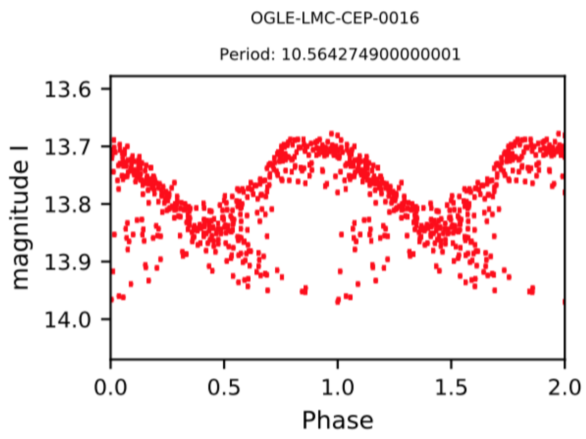


**Fig. 3.** OGLE-LMC-0016 Lightcurve with period 10.5642749. The shape indicated that the period is badly measured or maybe it does not correspond to a Cepheid

the B (420-720nm, blue) band, the other in the R (620-920nm, red) band. The total number of sources in the EROS-2 database is about 87 million consisting of 29 million in the LMC, 4 million in the SMC, 44 million in the Galactic bulge, and 10 million sources in the spiral arms. (Kim et al. 2014).
In this work we used data from EROS-2 through a project named EPOCH [4].

The EPOCH Project : EROS-2 Periodic Variable Star Classification Using Machine Learning, aims to detect and classify periodic variable stars in the EROS-2 light curve database including the Large/Small Magellanic Cloud (LMC/SMC), the Galactic bulge, and the spiral arm database. They use supervised machine learning methods to select/classify variable candidates.

The catalog contains 150,115 variable candidates selected from the 29 million EROS-2 LMC sources using the Random Forest method (Kim et al. 2014). Each source is cross-matched with 1) the MACHO and OGLE variable catalogs, and 2) the UCAC4, 2MASS, and SAGE catalogs. In 4 we can see the distribution of EROS-2 fields in the sky.

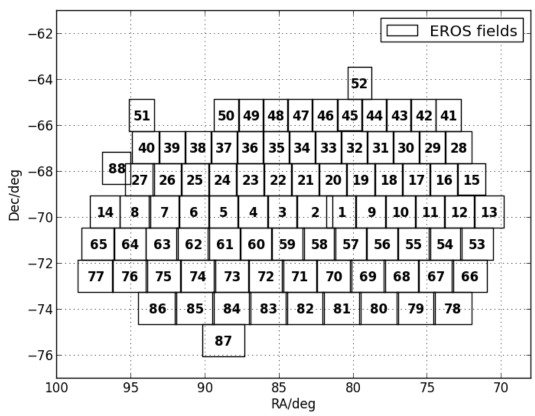


**Fig. 4.** EROS-2 LMC fields.

[4] `http://stardb.yonsei.ac.kr`

EPOCH found a total of 3869 object that were classified as Cepheid (pulsing in fundamental mode, first overtone and other), where 644 of these object were found just in EROS-2, the rest were cross-matched with other catalog.
It was decided to just consider light curves from objects that were detected by both projects, EROS-2 (through EPOCH) and OGLE.
In this work, the cross-matched object were rectified using cepheids coordinates data from OGLE.

In total there were found 412 cepheids in fundamental mode that were cross-matched with OGLE.

A comparison was realized in order to evaluate the difference between the period calculated for every of the 412 objects from the light curves used in EPOCH and the ones from OGLE. Result can be seen in Figure 5, it is possible to see a bigger scatter in $|P_{EROS} - P_{OGLE}|$ when period increases.

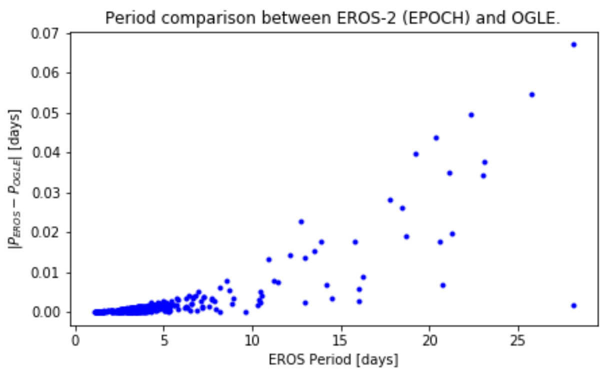


**Fig. 5.** Comparison between the periods calculated in EPOCH project (data from EROS-2) and the ones calculated in OGLE, for cepheids in fundamental mode.

### *2.3. MACHO*

The MACHO Project led by Charles Alcock (Alcock et al. 2000) is a collaboration between scientists in the bush. The Stromlo Siding Spring Observatory, the Center for Particle Astrophysics on the Santa Barbara, San Diego and Berkeley campuses of the University of California, and the Lawrence Livermore National Laboratory, which began in June 1992. Where the main objective of this project was to test the hypothesis that a significant fraction of dark matter in the halo of the Milky Way is composed of objects such as brown dwarf planets, white dwarfs, neutron stars or black holes: these objects they have come to be known as MACHOs; massive compact objects of the Halo. The signature of these objects is the occasional amplification of the light of the extragalactic stars by the effect of the gravitational lens. The amplification can be large, but the events are extremely rare: so it is necessary to monitor photometrically several million stars over a period of years to obtain a good detection rate. For this purpose, they have a two-channel system that employs eight CCD's of 2048 * 2048, mounted on the 50-inch telescope in Mt. Stromlo.

Analysis of a subset of these data has yielded databases containing light curves in two colors for 8 million stars in the LMC and 10 million in the bulge of the Milky Way. A search for microlensing has turned up four candidates to the Large Magellanic Cloud and 45 to the Galactic Bulge. Papers describing these results can be found in the Publications section of the MACHO (Web page)[5].

#### 2.3.1. MACHO: LightCurve Access

To obtain specific light curves in MACHO: First download the list of the coordinates of the center of the MACHO field and the identification of the field of the superposition of the region of the sky of interest, in this case for LMC: 1-99.

The coordinates of the sky of each star in a field are found in a CSV file that gives the identifier (field, tile, sequence) of the star of interest in the part of the contacts MACHO star, to do it more easily together with the 82 files corresponding to a single one in order to make a crossmatch with the coordinates of the Cepheids given by OGLE4 occupying TOPCAT.

Using the previously obtained field and tile identifiers, the MACHO photometry files are downloaded, which have several quantities available in addition to the two instrumental quantities. These include estimated errors, marks indicating possible problems with the particular data point, and information about the observation that generated the data.

#### 2.3.2. MACHO: Modified Julian Date: $MJD = JD - 2400000.5$

Given that the MACHO observation dates are in MJD, for the time measurements to be consistent with the other databases it was necessary to implement an astropy function that would allow us to go from JD to HJD, where JD was first obtained by adding the value of 2400000.5 and later the value given by the function is added, finally the value of 2450000.0 is subtracted, obtaining the observation date in $HJD - 2450000.0$

### *2.4. DASCH*

DASCH is the acronym for *The Digital Access to a Sky Century @ Harvard* [6]. This is a survey that digitalize photometric plates from 1885 to 1992, i.e, there is information for over a century of some stars. To the date, they have scanned over 358,000 plates all over the sky. The data releases are organized in a way that they scan all galactic longitude by 15 degrees of galactic latitude each time. Besides, they have identified 5 interesting areas in the sky which are called *development fields*. They are M44, 3C273, Baade's window, Kepler field and the LMC. Is this last development field we will focus on.

#### 2.4.1. LMC in DASCH

As we can see in 7, the coverage area of the LMC is about 5 degrees in radius. Also, we can see that the number of plates that contains dimmer stars decreases rapidly. We can attribute this to the fact that photometric plates were not as sensitive or efficient as modern CCD detectors, or that the size of the telescopes didn't make possible to reach higher magnitudes. If we compare 7 with Fig. Fig. 6, we can see that in the latter there are about 30 times more plates with stars than in the first.

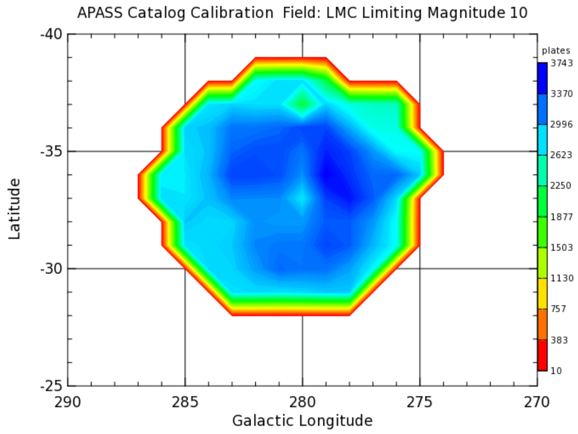


**Fig. 6.** Number of plates with limiting magnitude 10 of LMC at DASCH

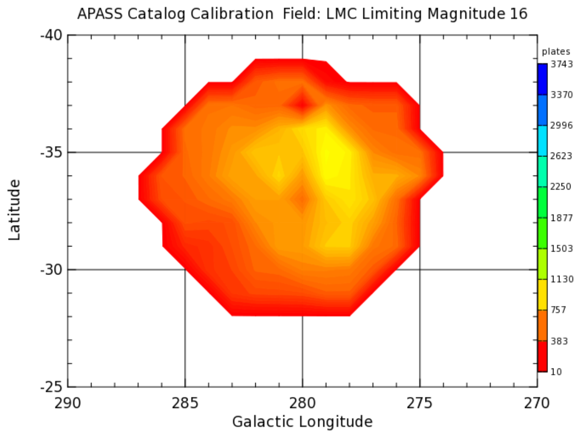


**Fig. 7.** Number of plates with limiting magnitude 16 of LMC at DASCH

#### 2.4.2. Access to light curves

The access to light curves is straightforward. You access to DASCH website (see footnote) and you can program several parameters. You need to give the coordinates in RA and DEC (J200) of the star you are interested in. Additionally, you can set a lower limit to the number of observations and a radius from which the star centroid matches to the coordinate you entered. Finally, you can choose the photometric callibration you want to use. In our case, we used no less than 50 observations within a 3 arcsec radius of coincidence, with APASS photometric callibration, i.e, B-band.

Then, the website look to every measured magnitude and display a preliminary light curve, and you can download the data in several formats. The drawback of this interface is that you need to download each star individually, or at most you can download 10 stars at the same time.

[5] `http://www.macho.anu.edu.au/Project/Overview/status.html/`

[6] For more information visit `http://dasch.rc.fas.harvard.edu`

### 2.4.3. Light curves

One of the huge advantages that DASCH offers in contrast with other surveys it that it can reach lower magnitudes, i.e, brighter stars, that in deeper surveys as OGLE are mostly saturated and therefore they do not count with reliable data. This is the case for OGLE-LMC-CEP-0619, that it is too bright that OGLE cannot reach it. We can see it's light curve on Fig. 8.

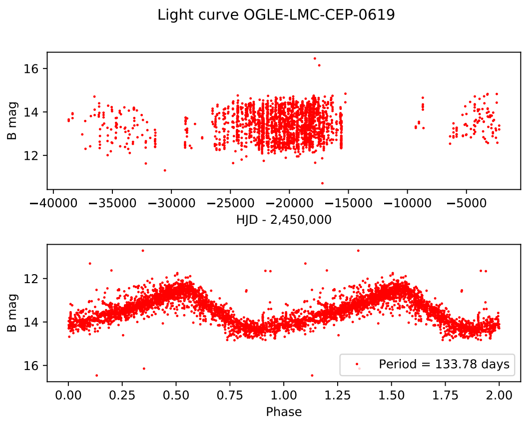


**Fig. 8.** Light curve of OGLE-LMC-CEP-0619. Upper: magnitudes as functions of HJD - 2,450,000. Lower: Phased lightcurve with OGLE IV period.

As we already stated, now it's cleat that we can have an enormous ammount of data distributed along many years. In the case of OGLE-LMC-CEP-0619, we can see that it covers ~35,000 days, which are equivalent to ~95 years.

However, not all light curves are as clear as this one. As we go down in brightness, the dispersion of data becomes important. On Fig. 10 we can see that the LC is not distinguishable at all due its high dispersion. Other interesting case is the case of Fig. 9, where we can see that DASCH data only captures the maximum brightness.

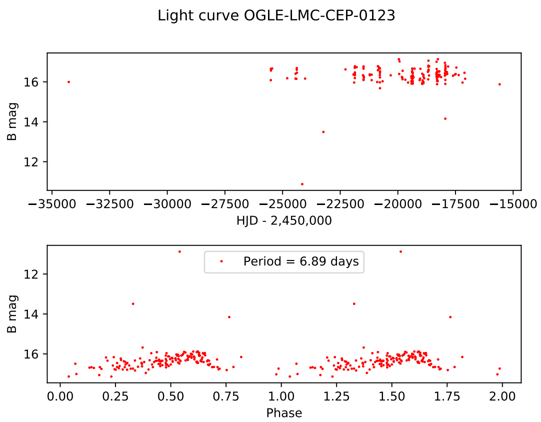


**Fig. 9.** Light curve of OGLE-LMC-CEP-0123. Upper: magnitudes as functions of HJD - 2,450,000. Lower: Phased lightcurve with OGLE IV period.

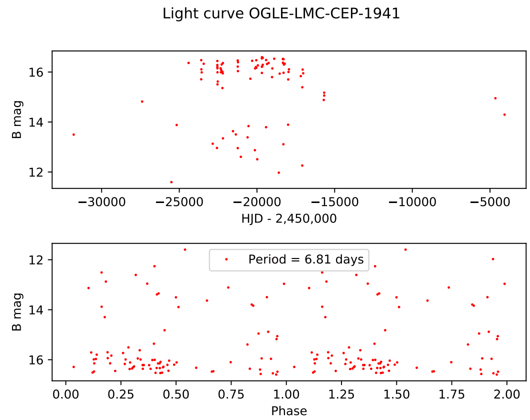


**Fig. 10.** Light curve of OGLE-LMC-CEP-1941. Upper: magnitudes as functions of HJD - 2,450,000. Lower: Phased lightcurve with OGLE IV period.

### 2.5. *Final Data*

Finally the final data contains 2435 Cepheids, with 1152 stars from MACHO in b and r, 412 stars from EROS in B and R, and 373 stars from DASCH. Only 53 contains data of OGLE, DASCH and EROS, 152 from OGLE, DASCH and MACHO and finally 100 from OGLE, EROS and MACHO.

The description of how many data contains each Classical Cepheid from OGLE-IV from other surveys is in *ident.dat*.

## 3. Matching and mixing light curves

Once we had every survey covered, we matched the data. We faced to main problems. First, all photometric bands were different, therefore the shapes and magnitude callibrations are not the same. The second one is that we need to match them together with the less dispersion possible in order to compute the O-C diagram, labor of group 2.

To solve this, we normalized by amplitude the lightcurves to the one that has OGLE-LMC-CEP-0012, which is 0.691 mag on I band at OGLE survey. Every band of every survey was directly scaled to that magnitude.

Next, we need to move the lightcurves to the same zero point, and the most natural way to do it is to center it around zero. So, we computed the mean magnitude of every lightcuve of every survey and then substracted it to each point. We can see the results on 11, where we show how the mixed data of OGLE and DASCH matches.

## 4. Periods

In other to calculate the differences in the period of the stars during the totality of the epoch conforming the lightcurve, it was implemented 3 different codes that attempt this.

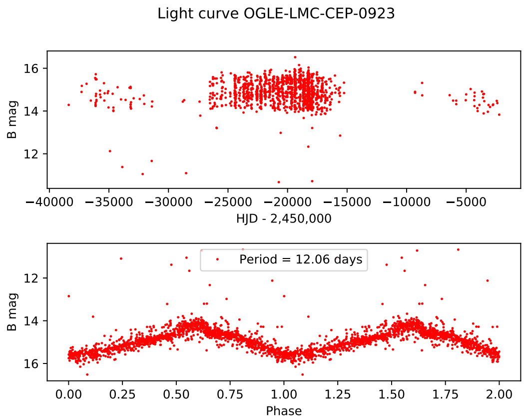


**Fig. 11.** Light curve of OGLE-LMC-CEP-0923 which has DASCH and OGLE data. Upper: magnitudes as functions of HJD - 2,450,000. Lower: Phased lightcurve with OGLE IV period.

### *4.1. First Code: Only OGLE*

As it was discussed in Section 2.1, there were 722 cepheids that had photometry in I and V available in since OGLE-II, that means since 1996. Since much of the stars only contain photometry from OGLE, the first attempt was to only analyse changes in periods from these stars.

A code was made in other to see if period calculated from OGLE-IV ident.dat was compatible. The result was that nearly all the stars have nearly the same shape of their lightcurve from the data of OGLE-II and OGLE-IV. For example OGLE-LMC-CEP-0610 with period 2.8880890999999997, in Figure 15:

This means there were not a change in the period between 1996-2000 in comparison with 2010-2015.

### *4.2. Second Code: Only DASCH*

In the Figure 12 it can be seen that the biggest concentration of data from DASCH is between HJD 2425000.0 and 2434500.0, which are the years 1921 and 1954 approximately.

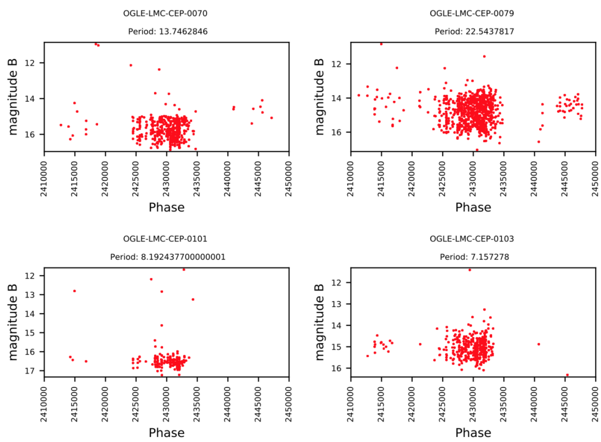


**Fig. 12.** Dasch epoch (HJD) versus magnitude B

The same attempt was made, and the periods from OGLE-IV were used in other to made the lightcurves of the data from DASCH.

At first, the light curves were made with the information of every epoch from DASCH, for example, see Figures 16 and 17:

From Figure 16 it can be appreciated that the period from OGLE can be adjusted to the data from DASCH, at least a lightcurve can be distinguished. However, it can also be perceive the dispersion of the data. This could mean that there is a very small change of period since the data from OGLE, but not necessary since light curves are not always as smooth as OGLE light curves.

In other to eliminate the other possibilities, because maybe this effect was because the big gap between the epochs, the light curves was plotted again, this time in a range of period. First, between the epochs 2425000.0 and 2434500.0 and then between 2430000.0 and 2431000.0, which were the epochs with the biggest among of data, and it is expected that the data do not change in a period of 1000.0 days but maybe change in comparison of the lightcurve with the data of 2010-2015. See Figures 18 and 19

For Figures 16, 18 and 19, it was used different algorithms for detecting and characterizing periodic signals, such as Lomb Scargle and BoxSquare. However, all of them returned periods that were the same (nearly the same) period from OGLE or not compatibles, probably because of the dispersion. However, we consider that using templates, deleting data or adding data between gaps is not a good idea, since we want to find differences in the periods and therefore we can not force the data so that the light curve takes a form concrete.

### *4.3. Third Code: Normalization*

We have to remember that the shape of the light curves change as we change bands. So in this section it will be analyzed how the light curves in Eros and Macho change if there are normalized with the others or with their magnitude. OGLE-LMC-0049 is a perfect example since it have data in EROS and MACHO. The results can be seen in Figures 20 and 21 for MACHO and in Figures 22 and 23. The light curved of OGLE-LMC-0068 from the data of Dasch, but normed, was also included for completeness. The light curve of OGLE-IV is figure 13.

As same as in 4.1, The light curves from MACHO and EROS have the same shape as in OGLE-IV. Since the data from OGLE II was measure nearly the same years that MACHO and EROS, it is consistent with what was obtained in the 4.1, that the periods of this Cepheids had not change since the 90's. The shape change in r from Macho but that was expected because it is a different band from I.

## References

Joshi, Y. & Panchal, A. 2019, AA,
Riess, A., C. S. Y. W. M. L. & Scolnic, D. 2019, ApJ, 876, 13
SoszyÅski, I., Poleski, R., & Udalski, A. 2008, Acta Astr., 58, 163

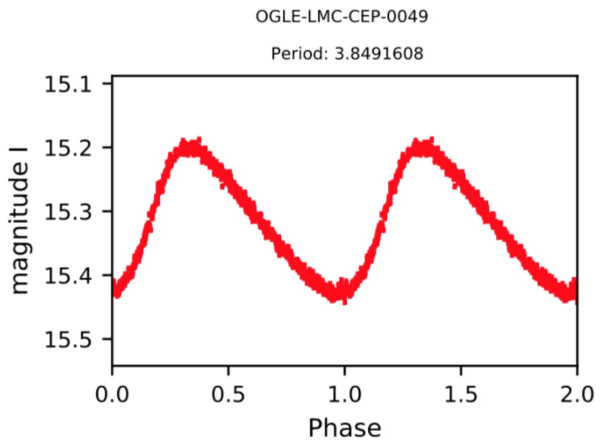


**Fig. 13.** OGLE-LMC-0049 in OGLE-IV

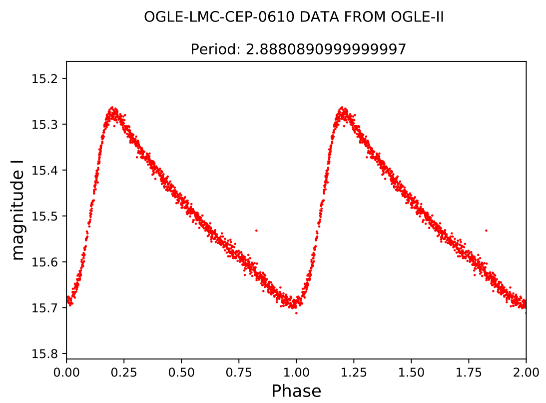


**Fig. 14.** OGLE-LMC-CEP-0610 photometry in I from OGLE-II.

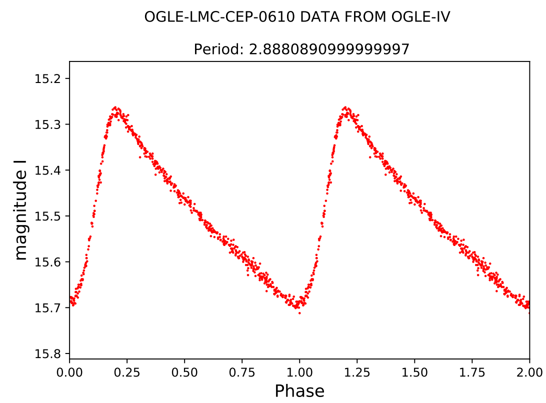


**Fig. 15.** OGLE-LMC-CEP-0610 photometry in I from OGLE-IV.

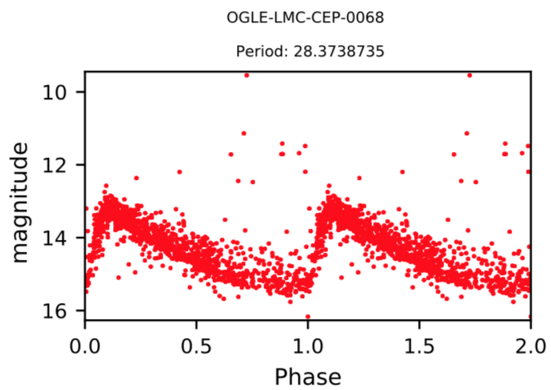


**Fig. 16.** OGLE-LMC-CEP-0068 photometry in B from DASCH

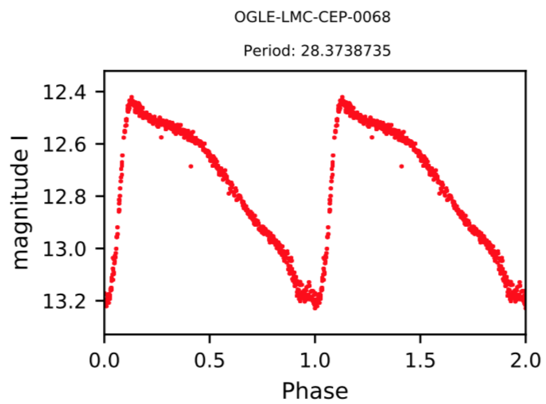


**Fig. 17.** OGLE-LMC-CEP-0068 photometry in I from OGLE-IV.

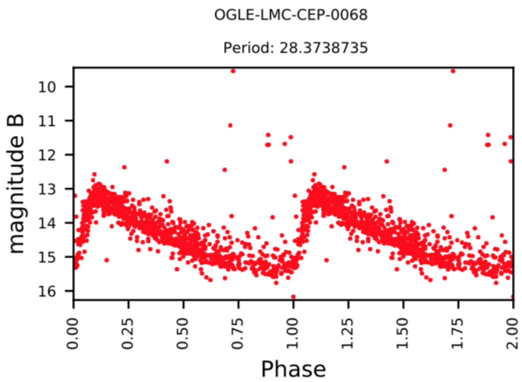


**Fig. 18.** OGLE-LMC-CEP-0068 photometry in B from DASCH between HJD 2425000.0 and 2434500.0

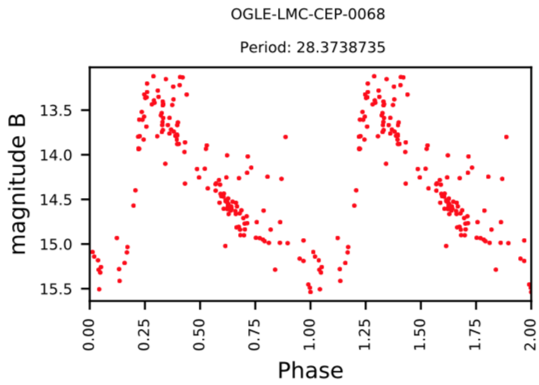


**Fig. 19.** OGLE-LMC-CEP-0068 photometry in B from DASCH between HJD 2430000.0 and 2431000.0

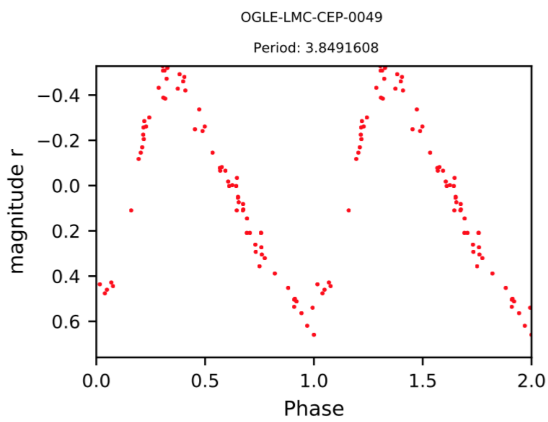


**Fig. 20.** OGLE-LMC-CEP-0049 photometry in r from MACHO normed as explained in Section

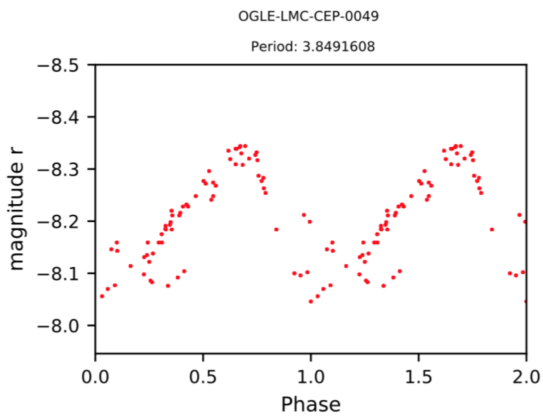


**Fig. 21.** OGLE-LMC-CEP-0049 photometry in r from MACHO not normed

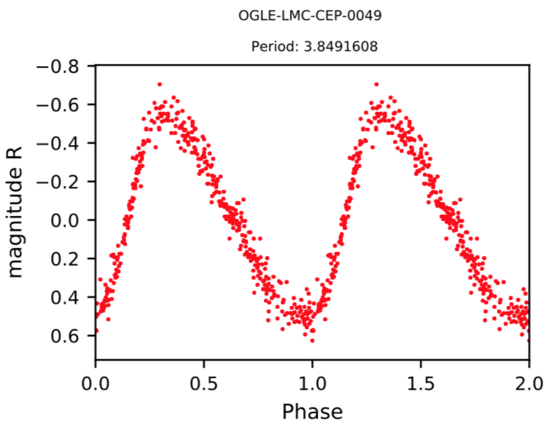


**Fig. 22.** OGLE-LMC-CEP-0049 photometry in r from MACHO normed as explained in Section

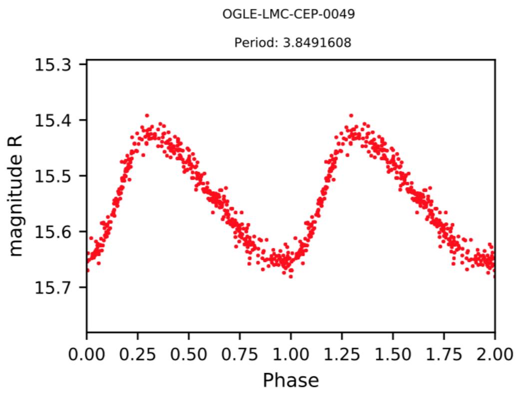


**Fig. 23.** OGLE-LMC-CEP-0049 photometry in r from MACHO not normed

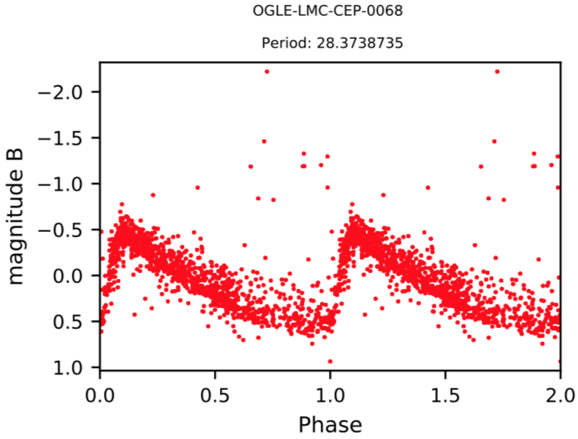


**Fig. 24.** OGLE-LMC-0068 normed, from the data of Dasch. It can be appreciated that it does not differs from the others in Section 4.2