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Cepheids from the EROS-2 Microlensing Survey

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Abstract. Using observations obtained in the pilot campaign of the EROS-2 microlensing survey we observed 290 Cepheids towards the LMC and 590 Cepheids towards the SMC. We present the constraints they give to stellar pulsation theory. We detect a statistically significant break in the slope of the period–luminosity relation for SMC fundamental mode Cepheids with periods shorter than 2 d and discuss its origin.

1. The EROS-2 Microlensing Survey

EROS (Expérience de Recherche d'Objets Sombres) is a French collaboration between astronomers and particle physicists to probe the Galactic halo, and the Galactic structure via microlensing. EROS has been operating between 1990-1994 using the ESO Schmidt telescope, and a 16 CCD mosaic on a 40-cm telescope mounted "on the back" of the GPO (Great Prism Objective) at ESO la Silla (Beaulieu & Sasselov 1997, and references therein). EROS was upgraded in 1996 and entered the EROS-2 phase. The prime focus of the Marly 1.0-m telescope at ESO La Silla is equipped with a focal reducer and a dichroic beam splitter with a mosaic of eight 2048 × 2048 CCDs in each channel. The total field is 0.7° × 1.4°. Data collection started in 1996 July for a minimal observing period of 6 yr. EROS-2 is primarily aimed at the search for microlensing events, and variable stars are only by-products of the experiment. Observations are made in several lines of sight: towards the LMC (60 fields), the SMC (10 fields), the Galactic center (67 fields), and 24 fields in the galactic plane (γ and β Scuti, γ Normae and θ Muscae).

The real strength of microlensing experiments is to realize a systematic photometric survey of millions of stars over long period of time (Beaulieu & de Wit 1999, and references therein). However, the filters adopted for the EROS-2 survey are the result of the convolution of the transmission of the dichroic in each path and the CCD response, giving a transmission of $V_{\rm EROS}$ 420-720 nm and $R_{\rm EROS}$ 620-920 nm. These filters are so wide that a reliable transformation between this system and a standard $UBVRI$ will be very difficult to determine. EROS-2 generates a very large, homogeneous database in its own photometric system, but comparison with other observations, models, and temperature calibrations are not at all trivial. We underline that these filters are different from the ones used during the EROS experiment (1990-1994), which were closer to a standard system.

2. The Cepheid Catalogues

The Cepheid period–luminosity ($P-L$) relation has been one of the corner stones of distance determination since early in the 20th century. It is the result of the projection of the instability strip in the $P-L$ plane. This statistical relation is therefore deeply linked to the actual shape of the instability strip itself. The different microlensing surveys have dramatically improved the number of available short period Cepheids toward the Magellanic Clouds.

A Cepheid envelope is an acoustic cavity in which a vast number of pulsation modes potentially exist. However, very few of them contribute to the dynamics of the system: only the unstable modes, and the marginally stable modes c oupled by resonances to unstable modes. Resonances are known to play an important role in shaping the light curves. Therefore, an analysis of the shape of the light curves will give us some information about the dynamics of these stars.

During the "EROS" era, we have built catalogues of variable stars in the LMC and in the SMC using the CCD data from the 1991-1994 campaign. A differential study of about 550 Cepheids from the LMC and SMC has been conducted to derive constraints on stellar pulsation theory (position of resonance centers, and beat Cepheids) and to find a subtle metallicity effect on the $P-L$ relation (Beaulieu et al. 1995, 1997a, 1997b, Sasselov et al. 1997).

From 1996 October to 1997 February a dedicated Cepheid campaign was undertaken in order to compare the Cepheid populations in the two Magellanic Clouds in the spirit of our earlier studies. During this period two fields in each Cloud were monitored about nightly. A total of 130–150 images was obtained for each of the four fields. The fields cover an area of $2° \times 2°$/cloud in the center of each Cloud. The exposure time was 20 s.

The photometry has been undertaken using the standard EROS-2 photometry package Peida++. After a massive photometric reduction we obtained 1,134,000 light curves of stars toward the LMC and 504,000 light curves of stars toward the SMC. In these two datasets a systematic search for periodic variable stars was performed (for $P > 0.5$ d) using the algorithm proposed by Scargle (1982). We fitted a $5^{\rm th}$-order Fourier decomposition of the form $X_0 + \sum_{i=1}^{5} X_k \cos(k\omega_k t + \Phi_k)$ to the light curves, and calculated the intensity-weighted mean magnitudes in each band, the phase difference $\Phi_{k1} = \Phi_k - k\Phi_1$, and the amplitude ratio $R_{k1} = X_k/X_1$. The Cepheid candidates were extracted using selection criteria in the color–magnitude plane and the period–luminosity plane. Using the Fourier coefficients determined above, it was possible to distinguish between classical Cepheids pulsating in fundamental mode (F), and s-Cepheids pulsating in a first overtone mode (1OT) as done in Beaulieu et al. (1995) following the suggestion of Antonello et al. (1986). Finally, a visual inspection of the selected Cepheid candidate light curves was undertaken in order to remove the clearly non-Cepheid variables and stars with a low signal to noise ratio, and to check for the F or 1OT nature of ambiguous candidates. The new EROS-2 Cepheid catalog (Afonso et al. 2000) consists of 590 Cepheids toward the SMC (351 F and 239 1OT Cepheids) and 290 Cepheids toward the LMC (177 F and 113 1OT Cepheids). In both LMC and SMC, 1OT Cepheids represent $\sim$ 40% of the samples. The light curves and Fourier coefficients for all the Cepheids from LMC and SMC are available on the EROS web site.

3. Some Constraints for Stellar Pulsation and Stellar Evolution Theories

From Fig. 1 one can extract the position of the center of resonances for LMC and SMC Cepheids. We found $P_0 \sim 10.5$ d in the LMC, and $P_0 \sim 11.5$ d in the SMC. However, this relies on a small number of stars; data from the full EROS-2, MACHO and OGLE-2 will be able to provide this result with better accuracy. The resonance center is shifted by $\sim$1 d between LMC and SMC. The nature of the Z-shape around 3 d for 1OT is less clear (see Moskalik et al. 2000). Is it the signature of a 2:1 resonance between the first overtone and the fourth overtone? The absence of the corresponding feature at the same period for radial velocity curves, as would be expected as a signature of resonance, is puzzling. The Z-shape is centered at $\sim$3.2 d in our Galaxy, $\sim$2.8 d in the LMC, and $\sim$2.2 d in the SMC. In fact, for the 10-d resonance, and the Z-shape, we do not provide new constraints compared to Beaulieu & Sasselov (1997), and Welch et al. (1997).

The observed $P-L$ relations show a sharp cut off at a given period. Below, only few stars are found, likely to be either first crossers, or stars in another evolutionary stage than the second or third crossing. Therefore, we can find the shortest period for F-mode pulsators of $P_0 = 1.85$ d in the LMC, and $P_0 = 1.1$ d in the SMC. It is more difficult to estimate the shortest period for 1OT pulsators because of the abundance at short period of beat Cepheids. (With this sample of EROS-2 data, we do not have a good efficiency to detect 1OT/2OT pulsators). On the other hand, it is known that the 1OT instability thins at long period. The longest period of 1OT is $P_1 = 5.8$ d in the LMC. However, there are just two stars from the 113 LMC 1OT pulsators with periods in the range 4.5-5.8 d, suggesting that the instability strip is still wide at 4.4 d, and thins at longer periods. The longest period of 1OT in the SMC is $P_1 = 4.2$ d. The $P-L$ relation is well populated up to this limit. The observed widths of the instability strip for fundamental pulsators in LMC and SMC are very similar. It is also the case for the first overtone instability strip of LMC and SMC.

4. Cepheid Period–Luminosity Relation

The $P-L$ relations for the F and 1OT Cepheids toward the LMC and SMC are shown in Fig. 2. A first inspection of these diagrams indicates a change in the slope of the $P-L$ relations for SMC F Cepheids with periods smaller than 2 d; this is visible in both colors, but more striking in R_{EROS} where differential reddening effects are smaller. The deviation of these short period Cepheids magnitudes with respect to an extrapolation of the $P-L$ relation for longer period Cepheids, reaches 0.2-0.3 mag at a period of 1 d. The SMC F Cepheids with periods smaller than 2 d are uniformly distributed in our field, and the slope break can be seen with smaller statistical significance in all sub-fields. The $P-L$ relation of the SMC 1OT Cepheids does not show such a strong slope break, although there is a hint of an effect around $\sim 0.72 \times 2 \approx 1.5$ d. Also, a

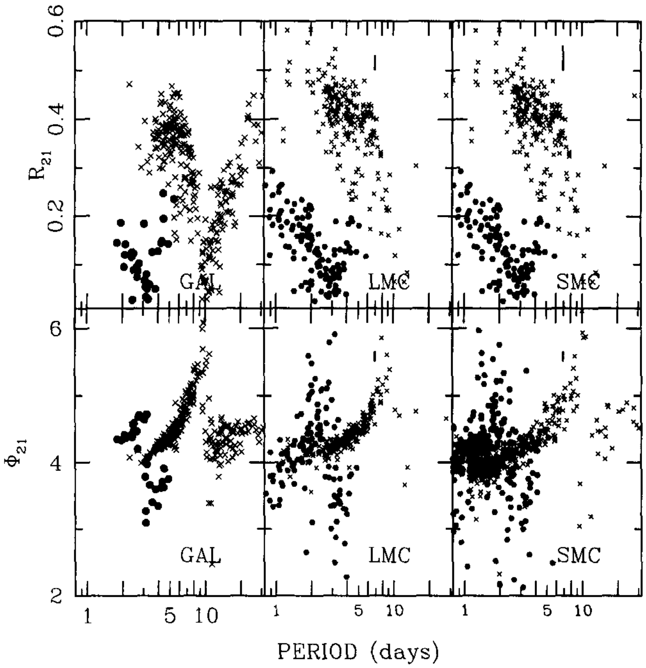

Figure 1. R_{21} and Φ_{21} as a function of period for fundamental (plotted as crosses) and overtone pulsators (plotted as filled circles) in the Galaxy (Antonello, private communication), LMC, and SMC from EROS-2 microlensing survey (Bauer et al. 1999). The vertical bar in the upper right corner of each panel is an indication of size of the typical error bar.

marginal deviation can be seen for LMC F Cepheids around 2.5–3 d. No notable deviation can be observed for LMC 1OT Cepheids.

In the following analysis the break-periods are defined as 2 d for SMC F Cepheids and 1.4 d for SMC 1OT Cepheids. In order to quantify the significance of the possible slope break, we fitted the $P-L$ relations in two different ways: (1) using a linear regression for the full data, and (2) using the following function: $f(x) = a + \beta_1(x - bp)$ for $x > bp$, and $f(x) = a + \beta_2(x - bp)$ for $x < bp$, where $x = \log_{10}(\text{period})$ and bp is the logarithm of the break-period (0.3 for F Cepheids and 0.14 for 1OT Cepheids). This second fit corresponds to a simultaneous linear regression of the upper and the lower part of the $P-L$ relation, imposing continuity at the break-period. In Table 1 we give the slopes obtained for these two types of fits for the SMC Cepheid F samples, i.e. method (1) all Cepheids, method (2) Cepheids with period greater than the break-period ($P > 2$ d) and Cepheids with period smaller than the break-period ($P < 2$ d). We do not give the result of the fit for 1OT since we do not find any significant slope break. We remark that the slopes of the LMC $P-L$ are comparable with the SMC $P-L$ with $P > 2$ d. These results are con firmed by OGLE-2 (Udalski et al. 1999).

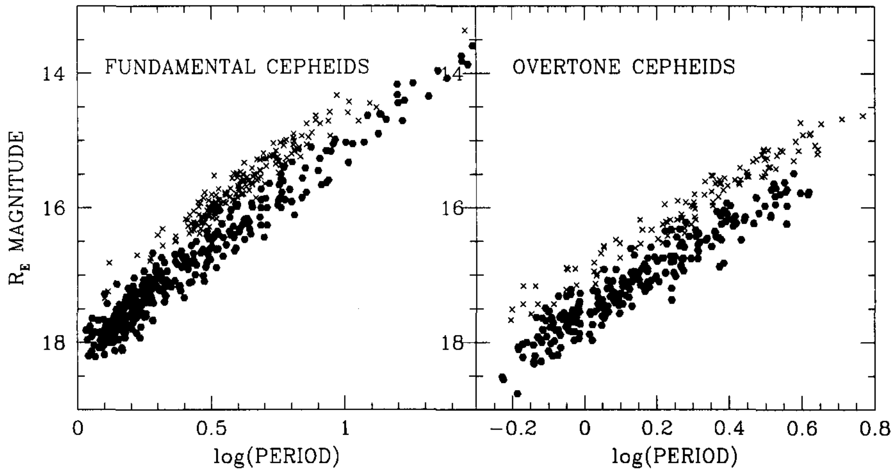

Figure 2. Cepheid $P-L$ relations for LMC (plotted as crosses) and SMC (plotted as filled circles) observed by EROS-2.

Several hypotheses have been proposed by Bauer et al. (1999) to explain the observed slope change of the $P-L$ relation for SMC F Cepheids and the absence of slope change for 1OT, whereas F and 1OT follow the same spatial distribution. One hypothesis is that it could be due to the decreasing extent of the blue loops at low masses: the blue loops would stop before reaching the blue edge of the fundamental instability strip, leading to a slope change of the $P-L$ relation. Baraffe & Alibert (2000) have computed evolutionary and pulsation models of Cepheids at various metallicities and report a slope change of the $P-L$ relation consistent with our observations. However, this hypothesis has to fulfill another important constraint: 1OT Cepheids are on average bluer than F Cepheids, thus a de-population of the 1OT instability strip should be visible at $\sim$ 1.4 d, and a slope break should be visible. The absence of such slope change for the 1OT variables challenges this explanation.

On the other hand, a speculative slope change of the F blue edge due to the physics of the stellar pulsation at a period of 2 d could generate the slope

Table 1. Slopes of the $P-L$ relation from EROS-2 Cepheids in V_{EROS} and R_{EROS}.

	α V_{EROS}	α R_{EROS}
LMC all	2.77 ± 0.07	2.89 ± 0.06
SMC all	2.91 ± 0.04	3.04 ± 0.03
SMC P<2 d	3.48 ± 0.19	2.95 ± 0.05
SMC P>2 d	2.80 ± 0.05	3.49 ± 0.16

change of the $P-L$ relation. This will have to be challenged by surveys of hydro models at low metallicity.

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Discussion

Pawel Moskalik: A comment on the location of the resonances: It is true for the f-mode Cepheids that ϕ_{21} drop indicates the position of the resonance. However, it is not the case for s-Cepheids. The resonance period is in fact located at much longer period. This can be shown with velocity data (see the poster by Kienzle et al., p. 239).