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THE EROS-2 LIGHT CURVE SERVER (ELCS), A TOOL FOR STELLAR ASTROPHYSICS AND SOME ASSOCIATED RESULTS

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Abstract. Between July 1996 and March 2003 the EROS-2 (Expérience de Recherche d'Objets Sombres) collaboration has conducted a large photometric survey mainly towards the Magellanic Clouds and the Galactic centre, in order to detect the baryonic dark matter in the Halo by microlensing effect. If it is now recognized that massive compact objects are not the major component of the Halo, tens of millions of light curves are now available for the stellar community. A specific server hosted by a CEA machine has been developped, in order to open a public access to these data. In its present configuration the so-called ELCS server contains more than 32 millions of Magellanic Clouds objects. The server is presented together with recent results of data mining in the EROS-2 database, including the detection of the first R Coronae Borealis stars in the SMC and a systematic search of double mode objects.

1 Introduction

The last decade of the twentieth century was that of the search of the baryonic dark matter in the Halo by means of the gravitational microlensing effect described by Paczyñski (1986). Several international collaboration groups were organised (MACHO, MOA, OGLE) to test this hypothesis that massive compact halo objects (the so-called machos) could be a major component of the dark matter halo of the Milky Way; in France the contribution to this research field was made by the EROS (Expérience de Recherche d'Objets Sombres) group composed mainly by CEA and IN2P3 physicists. The principle of these experiments was to record nightly the flux of tens of millions stars towards the Magellanic Clouds or the Galactic centre in order to have a chance to detect a few microlensing events. The EROS-1 version of the experiment was built in the beginning of the nineties around a 40 cm refractor mounted on the back of the GPS at the ESO Observatory (La Silla, Chile). After that the 1-m MARLY telescope was refurbished and replaced the GPS in 1996 for the EROS-2 configuration. The observations were conducted from July 1996 until March 2003.

The main result of the EROS-2 collaboration was to show recently after a thorough analysis of the seven-years data that machos in the mass range $0.6 \times 10^{-7} M_{\odot} < M < 15\ M_{\odot}$ are ruled out as the primary occupants of the Halo (Tisserand et al. 2007a). This result being acquired the question of the perennity of the data was open. They constitute a unique set of homogeneous photometric measurements on tens of millions stars that may be of interest for the stellar community. Thus is it worth developping basic tools to gain the public access to these data. Below is presented the first version of the EROS Light Curve Server (ELCS) containing the objects monitored towards the Magellanic Clouds.

2 The EROS-2 observational set-up

The Marly telescope is a one meter diameter Ritchey-Chrétien (f = 5.14m), equipped with two wide angle CCD cameras. Each camera is a mosaic of 8 CCDs, 2 along right ascension and 4 along declination. Each CCD has 2048 x 2048 pixels of $15 \times 15\ \mu\mathrm{m}^2$ size, corresponding to 0.602×0.602 arcsec^2. Images were taken simultaneously

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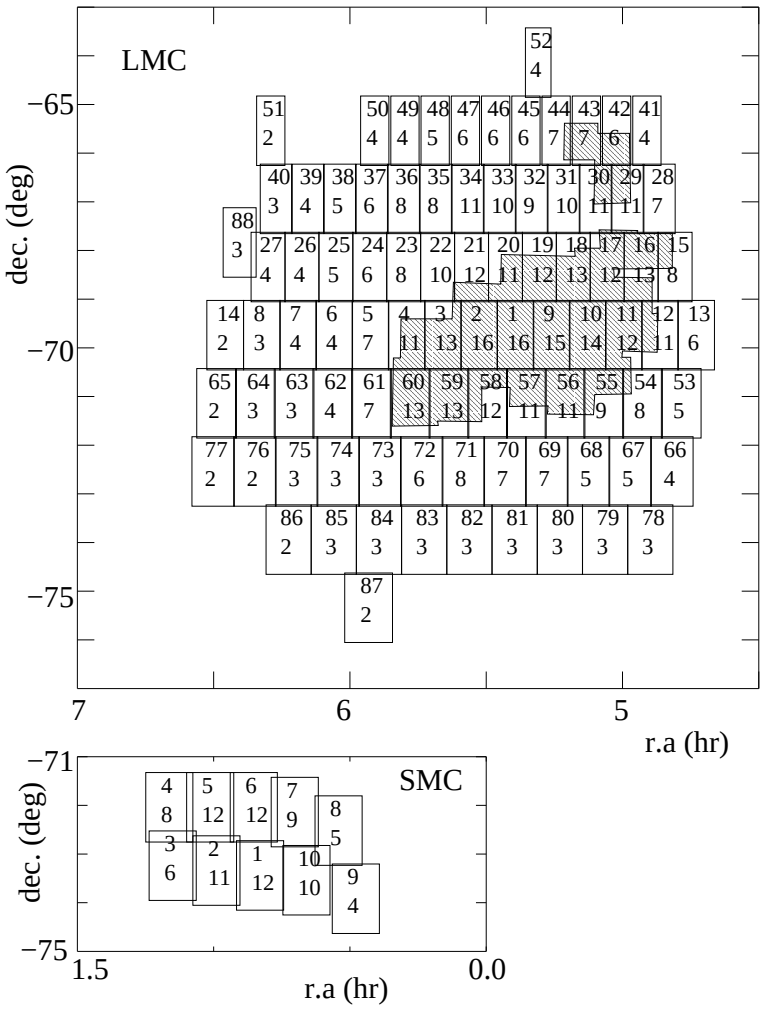

Fig. 1. Map of the EROS-2 LMC and SMC fields in equatorial coordinates. A total of 88 LMC and 10 SMC fields were monitored. The first number in each field is the field number and the second is the number of bright stars in the field in units of 10^4, as defined by Tisserand et al. (2007a). The two shaded regions (the larger one centered on the LMC bar) are the 13.4 deg^2 used by the MACHO collaboration (Alcock et al. 2000).

in two wide passbands, so-called $R_{\rm eros}$ centered close to the I_C standard band, and $B_{\rm eros}$ intermediate between the standard V_J and R_C bands. Almost all of our fields could be calibrated using stars from the catalogs of the Magellanic Clouds Photometric Survey (Zaritsky et al. 2004). For 4.5 deg^2, the calibration was checked with the OGLE-II catalog (Udalski et al. 2000). To a precision of ~ 0.1 mag, the EROS magnitudes satisfy

$$R_{\rm eros} = I_C \qquad B_{\rm eros} \;=\; V_J - 0.4(V_J - I_C)\;. \tag{2.1}$$

The observed fields correspond to 0.95 deg^2 each and they are twice as large in declination than in right ascension (1.38×0.69 deg^2). A total of 88 fields have been monitored towards the LMC and 10 towards the SMC. The positions of the fields are shown in Figure 1. The exposure times ranged from 180 s to 900 s. The fields have been sampled differently, according to their stellar density and distance from the optical centers of the LMC and the SMC. Broadly, there are three families of LMC fields : in the first 3 years of operation, 22 outer fields were seldom imaged, 22 fields were imaged about 100 times and the remaining 44 inner fields were imaged over 200 times. Later, from July 1999 on, all 88 LMC fields were imaged with a similar sampling. The number of photometric measurements, per star and per band, ranges from 300 to 600 in the LMC fields. The ten SMC fields were imaged with a similar sampling, except in 2001 and 2002 when the inner six fields were

imaged twice as often as the four outer ones. The number of photometric measurements, per star and per band, ranges from 600 to 900 in these SMC fields. The light curves of individual stars were constructed from fixed positions on templates using a software dedicated to the photometry of EROS-2 images (Ansari 1996). The stars were labelled according to the rules defined for the catalogue by Derue et al. (2002).

3 Description of ELCS

The EROS-2 Light Curve Server is organised around a file system managed by a dedicated computer connected to the CEA network. It contains at present 32 687 748 individual light curves organised as follows:

```
# star:  erosid     Ra     Dec     MagR   ErrMR   XR     YR   MagB   ErrMB   XB  YB
#  lm0014l35588 80.04221 -69.98160 18.997 0.327  811.4 1177.2 19.368 0.283  769.7 1215.2
#
#   date     FluxR ErFluxR FluxB ErFluxB ImageId
   294.91026 19.265 0.622 19.445 0.400 6g29117
   296.91696 18.924 0.471 19.078 0.368 6g31143
   301.92747 19.388 1.688 19.295 0.703 6h0569
   315.89025 19.222 0.801 19.518 0.610 6h1974
   317.82385 19.097 0.534 19.557 0.471 6h2190
   317.88745 18.907 0.279 19.488 0.304 6h21101
```

.....

The four first lines are comments giving the EROS-2 identifier (in the present case the 35588^{th} star of the field lm001, CCD #4, quadrant l), the J2000 decimal equatorial coordinates of the star, the mean magnitude, mean error and pixel positions of the star on the template image for the "red" channel, followed by the same quantities for the "blue" channel. Dates are given as HJD - 2 450 000. For each of them are reported the magnitude and error[1] for the "red" and "blue channels, followed by the EROS-2 internal identifier of the corresponding image (as an example `6g29117` is the 117^{th} image recorded in the night beginning the 29^{th} of July 2006).

Queries to ELCS are based on `wget`[2] commands. A wiki page is reachable at URL

`http://edbg.in2p3.fr:8080/wiki/Wiki.jsp?page=ElcsServer`

On this page some clients are available to get the data:

- `install_elcs`: this script will install the catalogues of stars on the user's computer in the directory defined by the `$EROS_CAT` environment variable. The size of this (gunzipped) directory is 2.68 Gb.
- `sky2eros`: this `tcl` script will download light curves of stars in a given region of the sky. The command `sky2eros -h` yields the different parameters:

```
usage: sky2eros [-v] [-q] [-nl] [-ms <maxstars>] [-cp <dist>] [-cr <raport>]
 [-i <datafile>] [<ra> <dec>]
-v             : mode verbose
-q             : mode quiet : aucune impression (sauf les erreurs)
-nl            : no lightcurves. Pas de recherche de courbe de lumiere dans le serveur.
-ms <maxstars> : nombre d etoiles proches du point demande (defaut : 3)
-cp <dist>     : coupure en proximite des etoiles proches, en arc sec (defaut : 20)
-cr <rapport>  : coupure sur le rapport de la distance a l etoile la plus proche
                        (defaut : 100)
-i <datafile>  : fichier contenant les etoiles a localiser dans la base EROS et de format
                                        <ident> <ra> <dec>
                                        <ident> <ra> <dec>
                                        <ident> <ra> <dec>
```

[1] Improperly called fluxes. This bug will be fixed in the next version of ELCS
[2] See http://www.gnu.org/software/wget/

```
                                        ......  .... .....

<ra> <dec>   : ascension droite et declinaison pour une etoile
(coordonnees horaires ou decimales)
(cet argument n'est pas obligatoire s'il existe un fichier <datafile>)
```

`sky2eros` also uses the EROS_CAT variable.

- `get_elc.sh`: this script returns in individual files light curves of objects whose internal EROS-2 identifier, as described by Derue et al. (2002), is known. Use the command `get_elc.sh -h` to get the different parameters.
- `getelcs.pl`: this `perl` script has the same use as `get_elc.sh` except that it displays on the standard output light curves delimited by `<light-curve> </light-curve>` tags. To save the ouput, redirect it in a file. A prerequisite to `getelcs.pl` is to install the `libwww-perl`[3] library.

4 Some results from mining the EROS-2 database

4.1 R Coronae Borealis in the SMC and in the Galactic bulge

R Coronae Borealis (RCB) stars are carbon-rich supergiants in a phase of rapid evolution. They are born-again giants for which two evolutionary scenarios have been proposed: either a merger of two white dwarfs or a final He-shell flash in a post-AGB star. They exhibit extreme and irregular changes in brightness, up to 8 magnitudes in visible light, caused by the obscuration of the stellar surface by newly formed dust clouds. They are rare objects: about 50 are known in the Galaxy although population estimates are of a few thousand. Furthermore, no Galactic RCBs have accurate distances so that the absolute luminosities of these variables are poorly known. This is why it is important to detect RCB objects in external galaxies, such as the Magellanic Clouds, whose distances are known. Studying RCBs in such low-metallicity systems is also crucial in order to better understand their evolutionary status and the time spent in the RCB phase.

We conducted a systematic search of RCB objects towards the SMC and the Galactic bulge. In the first case, we have identified the five first RCB stars discovered in the SMC (Tisserand et al. 2004) while in the second one we have obtained the identification of 13 new confirmed RCB stars and one new DY Per-like RCB. Figure 2 shows a $J-H$ versus $H-K$ colour diagram (Tisserand et al. 2007b). All the known RCB and DY Per type of star are represented. The black stars are the known galactic RCBs obtained from SIMBAD, CDS. The blue circles are RCBs found in the LMC (Alcock et al. 2001), the green squares in the SMC (Tisserand et al 2004) and the red triangles are the RCB stars recently found by Zaniewski et al. (2005). The 13 new EROS-2 galactic RCB stars and the new DY Per star are indicated with red dots. The DY Per class location is delimited with the dashed ellipse contour; it encloses also the expected area occupied by most carbon-rich stars. The dot curve correspond to the blackbodies combination of a 5500 K star and a 1000 K dust shell in various proportions ranging from all 'star' to all 'shell' from Feast (1997). The area delimited with straight lines represent the infra-red zone inspected in the 2MASS database. The line on the right side represents the reddening vector from Rieke & Lebofsky (1985). Also shown are the expected position (lines in the bottom-left side) for a large spectral type range of common dwarf (green) and giant (black) stars from Bessell & Brett (1988). Our study suggests that the new RCB sample is located inside the Galactic bulge.

4.2 Double mode (Beat) Cepheids in the Magellanic Clouds

The pulsation of a Beat Cepheid is either in the fundamental and the first overtone modes (FO/F), or in the first and second overtone modes (SO/FO). In the former case it is well known that the period ratio is dependent on the metallicity Z, this dependency appearing on the Petersen diagram (Petersen 1973) which shows the period ratio (second mode over first mode) *vs.* the period of the first mode. Using only the pulsational properties of 5 newly discovered BCs in M33 and with the help of stellar pulsation theory and of mass-luminosity relations,

[3] See http://lwp.linpro.no/lwp/

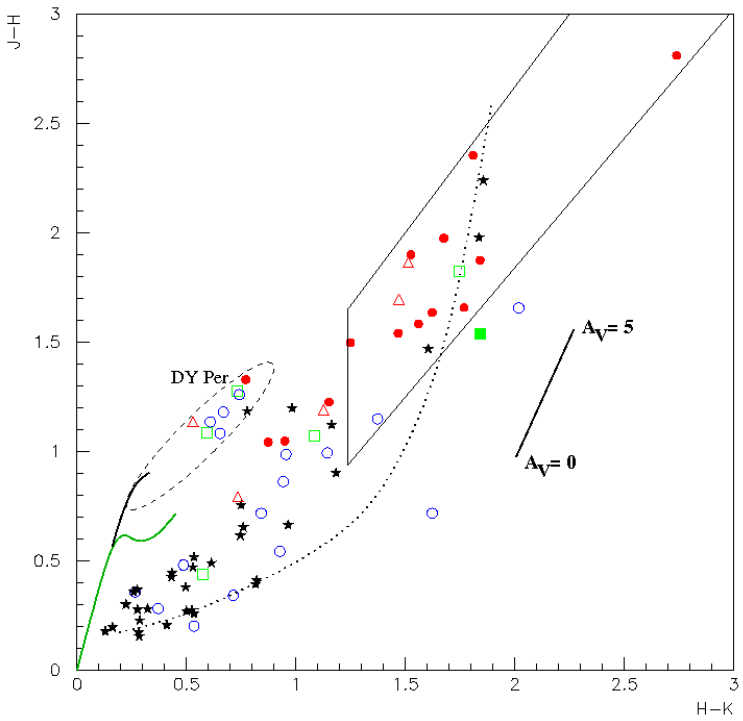

Fig. 2. $J - H$ versus $H - K$ colour diagram for known RCB objects. Symbols are defined in the text.

derived from evolutionary tracks, Beaulieu et al. (2006) have deduced a metallicity gradient of this galaxy in excellent agreement with the standard spectroscopic metallicity gradients that are determined from H II regions, early-B supergiant stars, and planetary nebulae. BCs are thus an additional and independent probe of galactic metallicity. We made a systematic search of Beat Cepheids in the Magellanic Clouds from the EROS-2 database. Numerous previously unknown objects have been detected and metallicity data are deduced from the FO/F BCs properties of both Clouds (Marquette et al. 2007). Figure 3 shows how FO/F Beat Cepheids are used as tracers of metallicity in their host galaxy by plotting a composite Petersen diagram of upper and lower values of metallicity computed by Buchler & Szabó (2007).

5 Perspectives

In the near future ELCS will be subject to changes in several directions. First, the integration of the catalogs to the VizieR CDS tool is planned, in such a manner that the final user will be able to match the EROS-2 objects with those of other catalogs. Second, it remains to include in ELCS the Galactic bulge photometry which will double at least the number of catalogued objects. And, last but not least, the mining of the EROS-2 database is not achieved. We expect that ELCS will bring new people to this stellar research field.

This paper is dedicated to the memory of Alain Milsztajn who passed away a few days before the Grenoble meeting. He was one of the historic founders of EROS and a particularly enthousiastic and active member of the collaboration.

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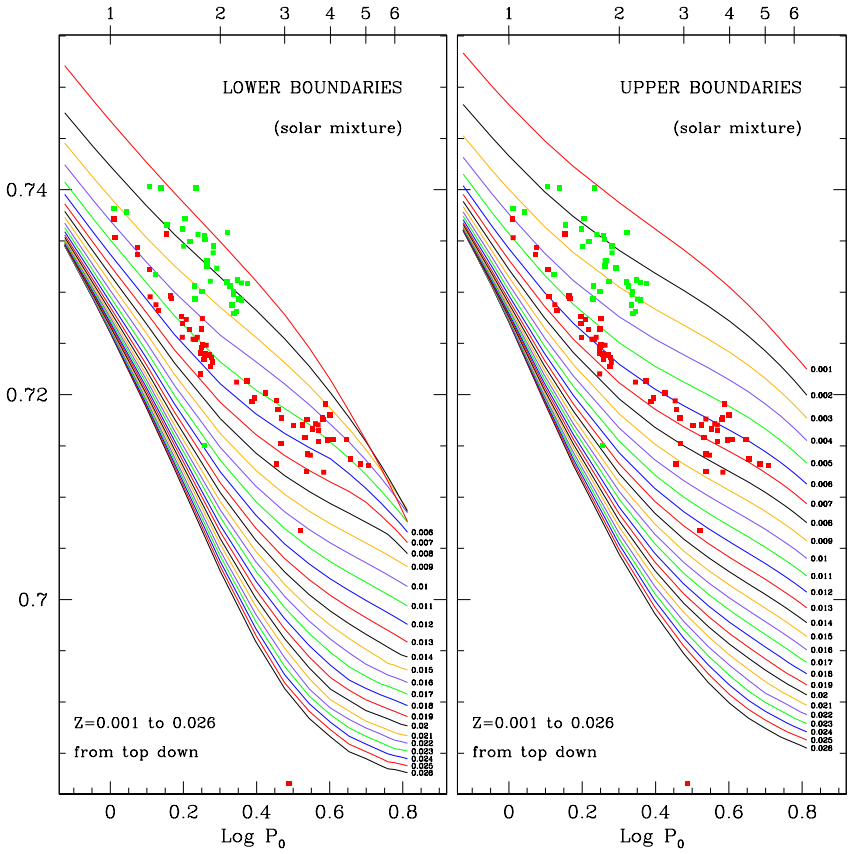

Fig. 3. Composite Petersen diagrams of FO/F Beat Cepheids in the Magellanic Clouds. Red symbols are for the LMC objects while green symbols are for the SMC ones. Lines represent locations of constant metallicity for the values indicated. P_0 (days) is the pulsational period of the fundamental mode.

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