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Stellar variability in low-extinction regions towards the Galactic Bulge*

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Abstract. Intensive monitoring of low-extinction windows towards the galactic bulge has provided in recent years valuable information for studies about the dynamics, kinematics and formation history of this part of the galaxy, mainly by characterizing the bulge stellar populations (Paczyński 1996). Since 1997, we have been conducting an intensive photometric-astrometric survey of the galactic bulge, with the monitoring of about 120000 stars in 12 windows uniformly distributed in galactic latitude and longitude (Blanco & Terndrup 1989; Blanco 1988) never before submitted to this kind of survey. For this purpose, we have used the IAG/USP CCD Meridian Circle of the Abrahão de Moraes Observatory. The main objective of this project is the identification and classification of variable objects. In this work we present the set up and development of the necessary tools for a project like this and the posterior analysis of our data. We briefly describe the construction of a program to organize and detect variables among the observed stars, including real time alerts (for variations greater than 0.3 magnitudes). The preliminary analysis after the processing of 76 nights of observation yielded 479 variable stars, from which 96.7% of them are new. We discuss the preliminary classification of these variables, based on: a) the observed amplitude of variation; b) the shape of light curve; c) the expected variable classes among our data and d) the calculated periods, whenever possible. Finally, we discuss the future perspectives for the project and for the applications and analysis of the discovered variable stars.

Key words: stars: variable general — techniques: photometric — galaxy: center

1. Introduction

The picture that we formed of the Galaxy suffered many modifications since the first analysis of the count of stars in the eighteenth century. After the discovery of the existence of large amounts of gas and dust, which causes light extinction and makes the observations of the center region of the Galaxy very difficult in several bands, the conclusion was that the Galaxy is of a spiral-type, with arms composed by metal rich young stars and a halo and the central region (bulge), constituted by metal poor old stars.

It was later discovered that the irregular distribution of dust and gas presents some "holes" where the extinction is considerably lower. The best known of these so-called *windows* has been found by Baade (1951) and extensively studied since then. Generally speaking, these low-extinction windows offer a unique opportunity to obtain information about the bulge in the optical range and compare this part of the Galaxy with the halo and disk (and with other galaxies). Great progress has been obtained by the observation of these regions and our picture of the Galaxy changed. For example, with the advent of direct measures of metal abundances of the K giants in the Baade window (Rich 1988), it was possible to conclude that the Galactic bulge is not a metal-poor structure: its mean metallicity is twice the solar neighborhood value. This means that the halo and the bulge are quite distinct structures. Today we know that in the galactic bulge reside stars showing a large range of metallicities.

However, many questions still remain open. The knowledge of the age of each galactic component is one of these and it is important to decide between the several formation scenarios: would the bulge be older than the halo, and if so by how much? How are these structures formed? Many authors have worked on these subjects. Terndrup (1988) estimated the bulge age using the color-color diagrams of four low-extinction windows, analyzing the position of the main sequence strip. He concluded that the bulge is between 11 and 14 Gyr old.

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* Tables 6–17 are only available at the CDS in electronic form only (ftp 130.79.128.5) or via http://cdsweb.u-strasbg.fr/Abstract.html

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In another work, Lee (1992) calculated the relative age of the RR Lyrae in the halo and in the bulge and found that bulge stars would be older than the halo RR Lyrae by 1.3 Gyr. The discovery of very old stars in the bulge does not necessarily mean that the bulge is the first structure to be formed, since the possibility of a merger population exists.

Recently, several works have shown the presence of a galactic bar in the bulge. Stanek et al. (1994), using the stars of the red clump, found an asymmetry in galactic longitude. Similar results were obtained with the hydrogen 21 cm line (Liszt & Burton 1980) and in 2.4 μm (Blitz & Spergel 1991). Whitelock & Catchpole (1992) detected a longitudinal asymmetry in the distribution of the Mira variables in the bulge. The actual extension and inclination of the bar are problems yet to be solved.

Many works help to solve this and other problems related to the galactic bulge may also be solved, provided adequate data is available. Besides their intrinsic interest as representatives of specific evolutionary phases, variable stars are one of the most valuable ones since they can be used as distance indicators, tracers of metallicity gradients and several other applications, being a very useful tool for galactic structure investigation.

Some massive monitoring programmes, as examples MACHO and OGLE groups, have been recently monitoring the bulge in search of microlensing events (see Paczyński 1996, for a review) with well-known success. The secondary products, complete catalogs of the monitored regions and the discovery of new variable stars, proved to be as interesting as the microlensing events themselves. However, most of these projects are indeed monitoring a limited area of the galactic bulge (in their first phases) in order to maximize the microlensing detection probability. Therefore, a wider coverage of stellar fields for other relevant regions is not attempted.

With these limitation in mind, we have developed and conducted a small monitoring project of 12 selected low-extinction windows from April 1997 until August 1998 (see Table 1). The windows were taken from the works of Blanco & Terndrup (1989) and Blanco (1988). In two successive campaigns we have used the recently refurbished Meridian Circle of the Abrahão de Moraes Observatory (operated by the IAG/USP) to observe these fields (see below). The main objective of the project was the discovery and classification of variable stars (in principle, for variations greater than 0.3 magnitudes), with the construction of a database that can be used by the astronomy community for several researches, as discussed above. The final goal will be to have an on-line, real time processing data to stimulate the study of potentially interesting events by other observing facilities. The first scientific result of the project has been a high-quality extension of the Tycho catalog for the observed regions (Dominici et al. 1999, hereafter Paper I), a necessary step to perform the data reduction. We should remark that this project was not appropriate for the search of microlensing events since the meridian circle allows the observation stars up to $V = 16$ approximately and the probability to detect this kind of effect is low.

The use of the meridian circle for photometry purposes was attempted previously by Henden & Stone (1998), who published a catalog of 1602 variable stars, of which only 85 were found in the literature. The observations which originated this work were performed by FASTT, which is very similar to our instrumental setup.

Many types of variables were expected to show up in our project. Since we were working with a small refractor instrument, only the brighter stars of the bulge, like the Miras, could be observed. Stars that are present in the disc, like classical cepheids are expected and the intermediate population (the transition between disc and bulge and between halo and bulge), like RR Lyrae and W Virginis, should be also present in the sample. Binary systems can be found in all galactic regions along the sight of view, having a variety of magnitudes, periodicities and stellar components. Cataclysmic variables should be relatively rare but fully detectable with our instrumentation (Dominici et al. 1998a).

We shall describe in the next section the selected fields. Section 3 is devoted to a presentation of the instrumental facilities and data reduction method. The observational program and the differential photometry with the Meridian Circle are described in the Sect. 4. The development and tests of the program to organize and search for variable objects (*Class32*) is discussed in Sect. 5. The variable stars found and their classification and analysis methods are detailed in Sect. 6. Conclusions and future perspectives are presented in Sect. 7. The light curves examples in Appendix A, the catalogue of variable stars in Appendix B[1] and a brief description of the effects of the chromatic aberration in the meridian circle in Appendix C close the present paper.

2. Selection of the fields

With the aim of studying M giants in the galactic bulge, Blanco & Terndrup (1989) and Blanco (1988) collected from the literature, low-extinction windows evenly distributed in galactic latitude and longitude and selected new regions with analysis of old photographic plates. The distribution of the resulting 31 windows, that we adopted for our observational programme, can be seen in Fig. 1. Since we needed to develop the necessary tools and analysis methodology to start the project, we decided to use only 12 windows for the first stage of the work. Table 1

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[1] Tables B.1 to B.12 are only available in electronic form at the CDS via anonymous ftp to cdsarc.u-strasbg.fr (130.79.128.5) or via http://cdsweb.u-strasbg.fr/Abstract.html

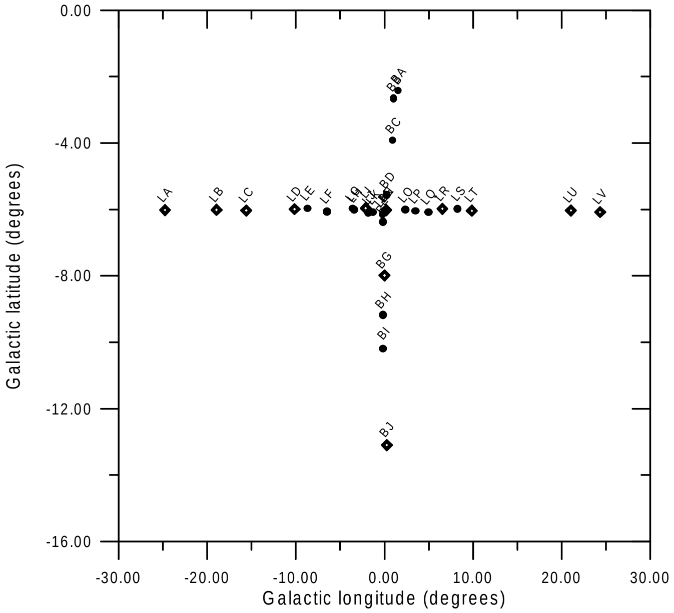

Fig. 1. Position of the center of the 31 low-extinction windows collected or discovered by Blanco & Terndrup (1989) and Blanco (1988). The hollow symbols indicate the 12 windows that we monitored in the first stage of the project

Table 1. Coordinates of the 12 low-extinction windows that we choose for monitoring in the search for variable stars

Window	#	α (J2000)	δ (J2000)	b (°)	l (°)
BE	5	18 10 17	−31 45 49	−6.02	0.20
BG	7	18 18 06	−32 51 24	−7.99	0.00
BJ	10	18 40 49	−34 49 48	−13.10	0.27
LA	11	16 56 57	−52 44 53	−6.02	−24.77
LB	12	17 18 27	−48 05 40	−6.01	−18.96
LC	13	17 29 22	−45 20 05	−6.03	−15.61
LD	14	17 44 59	−40 41 37	−5.99	−10.14
LI	19	18 04 48	−33 47 46	−5.96	−2.11
LR	27	18 23 32	−26 10 16	−5.98	+6.54
LT	29	18 34 09	−21 23 35	−6.04	+9.87
LU	30	18 51 26	−13 18 41	−6.03	+21.04
LV	31	18 57 37	−10 23 35	−6.08	+24.35

summarizes the list of these low-extinction windows, as displayed in Fig. 1.

The great advantage of this sample of windows is that they cover almost all bulge area. The monitoring programmes with the aim to discover microlensing events (MACHO and OGLE I, for examples) are concentrated in areas near the Baade window, basically in the interval $-6° < l < 6°$ and $-6° < b < -2°$ (Stanek et al. 1996; Bennett et al. 1994). In this sense, our shallower but spatially extended search can be considered as complementary of the massive databases of the central regions.

3. Instrumental facilities and data reduction

The Askania-Zeiss Abrahão de Moraes meridian circle, operated at the IAG/USP Valinhos Observatory ($\phi = 46° \, 58' \, 03''$, $\lambda = -23° \, 00'06''$), is a 0.19 m refractor instrument with a focal distance of 2.6 m. A CCD detector Thomson 7895A with 512 × 512 pixel matrix and a pixel scale of 1.5′/pixel was used for the imaging (Paper I, Viateau et al. 1999). The observations are performed in a drift-scanning mode. So the integration time, for a declination δ, is given by

$$t_{\rm int} = 51 \, \sec\delta \; s. \tag{1}$$

The observed field has a width of 13′ in declination by an arbitrary interval in right ascension (some minutes to several hours). It is possible to obtain images of several thousands of stars per night, up to magnitudes as faint as $m_{\rm Val} = 16.5$, depending on the transit time as reflected by Eq. (1) (we will use "$m_{\rm Val}$" to designate the magnitudes obtained with the Valinhos system ($V_{\rm V}$ filter) and "V" for magnitudes in the standard Jonhson system ($V_{\rm J}$ filter), see below).

The optimal magnitude interval for the observations is $9 < m_{\rm Val} < 14$, while the typical accuracy in the positions and magnitudes for a single measurement of a given night is shown in Fig. 1 of Paper I.

The filter we have used in this and other observational programmes is somewhat wider than the standard Johnson filter $V_{\rm J}$; allowing a larger coverage towards the infrared band in order to maximize the number of objects by taking advantage of the better quantum efficiency of the CCD in that region. Figure 2 of Paper I shows the response of the Valinhos filter $V_{\rm Val}$ together with the standard Johnson filter $V_{\rm J}$. The correlation between the filters, the method used for our programme and the limitations are described in Paper I. In the present work we have used the differences of magnitudes of the stars with respect to a standard reference set, as described in the next section.

The employed data reduction method requires a first step, where the sky background is subtracted by a linear polynomial fitted to each pixel column. Objects are identified when 3 consecutive pixels with a 2σ confidence level are detected, where σ is the standard deviation of the mean count rate in each column. A two-dimensional Gaussian surface is fitted to the flux distribution of the objects, to obtain the x and y coordinates of the centroid, the flux and respective errors (Paper I, Viateau et al. 1999). In the following step, the celestial positions and magnitudes are calculated by solving a system (Eqs. (3-5) in Paper I) with respect to reference stars (Sect. 4). For our variability analysis we take these results, i.e., those obtained in the classical way, night-by-night.

After this process, the system is again solved in an iterative process, now for all stars detected in the field, by a global reduction, using the field overlap constraint among all observation nights (Eichhorn 1960; Benevides-Soares & Teixeira 1992 and Teixeira et al. 1992). At each

Table 2. Initial and final observation sidereal time for the 12 windows chosen for the Valinhos monitoring programme

Window	Initial TS($^{\rm h\ m}$)	Final TS($^{\rm h\ m}$)
LA	16 54	17 00
LB	17 15	17 21
LC	17 26	17 32
LD	17 42	17 47
LI	18 03	18 06
BE	18 08	18 13
BG	18 16	18 20
LR	18 22	18 26
LT	18 32	18 36
BJ	18 39	18 44
LU	18 48	18 53
LV	18 55	19 00

step of iteration, the system is solved by least squares (Benevides-Soares & Teixeira; Teixeira et al. 1992). The process converges in a few iterations (typically less than 10 steps). This method is applied to obtain the best values to the positions, as can be seen in Appendix B.

4. Observational programme and the photometry with the Meridian Circle

The project was idealized to observe the selected windows in all nights of good weather, whenever the bulge was visible. Two campaigns were concluded: the first was between April and September, 1997 and the second was between April and August, 1998. The average size of the (irregular) fields was 3 to 6$^{\rm m}$ in right ascension and 13$'$ in declination (see Table 2).

Since the two refracting objective presents considerable secondary chromatic aberration, the spectral band should be centered around the focal minimum at λ = 498 mm. The CCD response peak at 700 mm and a filter was added to create a final spectral band between 500 and 900 mm. The spectral limitations prevent the use of a second color band filter.

Initially, we had to face the problem that the total number of reference stars of the usual (astrometric) catalogues inside the defined fields is small. This posed a serious difficulty for data reduction and the search for variable objects. As a first step towards a comprehensive study of the windows, we have attempted to construct dense (secondary) reference catalogues, based on Tycho catalog (ESA 1997), intended to be of general use. Methods and final catalogs are given in Paper I. For their construction we needed to make "long" exposures of about 1 hour in right ascension to include as many Tycho stars as possible in each field. During the first 1997 campaign we performed 5-6 "long" frames for each window. Tycho catalogue was extended for stars up to $m_{\rm Val}$ = 13, limited to the non-variable stars. A summary of the results, with the mean precision and the number of secondary reference stars obtained for each window is presented in Table 3.

Table 3. Average position and magnitude precisions for secondary reference stars in the low-extinction windows (mean epoch JD 2450612). Last column indicates the number of reference stars in the final catalogs

Window	$\sigma_\alpha(^{\rm s})$	$\sigma_\delta('')$	$\sigma_{m_{\rm Val}}$	$\sigma_{\rm w}$	N
BE	0.0017	0.015	0.028	0.0043	60
BG	0.0021	0.014	0.026	0.0040	41
BJ	0.0021	0.013	0.027	0.0041	43
LA	0.0019	0.011	0.035	0.0038	55
LB	0.0019	0.011	0.033	0.0039	36
LC	0.0014	0.011	0.029	0.0035	61
LD	0.0015	0.011	0.027	0.0036	47
LI	0.0010	0.011	0.031	0.0038	20
LR	0.0025	0.014	0.031	0.0048	37
LT	0.0021	0.014	0.028	0.0049	32
LU	0.0017	0.013	0.028	0.0045	31
LV	0.0015	0.016	0.034	0.0048	44

At the end of the two campaigns, we had collected a total of 76 nights with best quality images (average of 35 observations per window).

It is useful to remark that some standard steps in the frame treatment for photometry (flatfield, bias) are not necessary nor possible in our case: in drift scanning observation mode each "pixel" actually corresponds to a combination of 512 pixels, and then, even if the response of each elementary pixel is known to be non-uniform, the final result is the column-wise sum over the CCD 512 pixels width (the columns are parallel to the image motion). The summed line so obtained displayed an essentially constant response during several flatfield measurement tests, so that the field correction can be dropped.

Given that the integration time is limited by the time of stellar transit, the telescope is small and the site quality is not very high, we could only observe stars up to $m_{\rm Val} < 16.5$, approximately. Therefore, we can detect only to brightest bulge stars and most of the monitored stars are actually foreground objects. The completeness of the sample for BE window is shown in Fig. 2. The maximum of the histograms for each window can be seen in Table 4.

With the aim of removing systematic errors, we worked with the difference of magnitudes with respect to the mean magnitude of the reference stars in the field which compose the secondary references catalogues presented in Paper I (or *differential magnitudes*). The idea was to remove systematic errors due to observational conditions that affect in much in the same way the reference stars, as

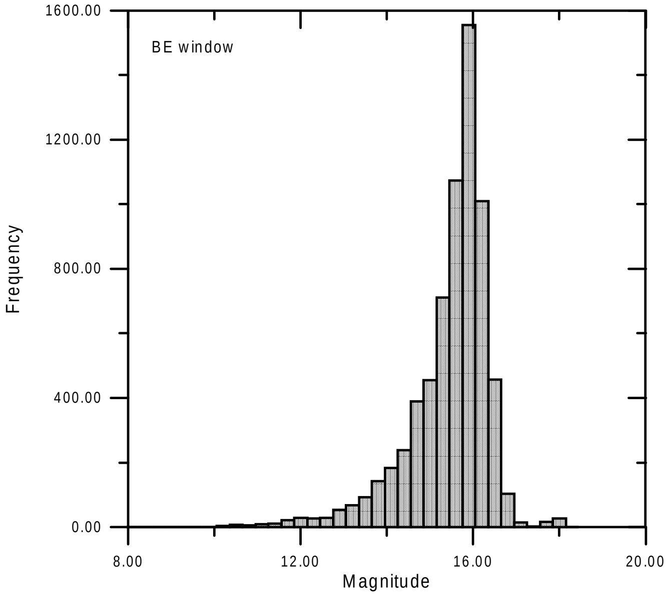

Fig. 2. Completeness of our sample in the BE window

Table 4. Completeness of the sample for the monitored 12 low extinction windows. The $Mag_{\max}$ column indicates the faintest objects detected for the region and the $Hist_{\max}$ column gives the magnitude corresponding to the largest frequency

Window	$Mag_{\max}$	$Hist_{\max}$
BE	18.3	16.0
BG	18.2	16.0
BJ	18.1	16.0
LA	18.4	16.4
LB	18.3	16.2
LC	18.2	16.2
LD	18.2	16.0
LI	18.2	15.8
LR	18.1	16.0
LT	18.1	15.6
LU	18.1	16.0
LV	18.0	16.0

well as all other objects in the field. It should be stressed that, in general, this removal procedure is more efficient when the comparison reference stars have magnitudes and colors comparable to the field stars and, therefore, in our case the use of differential magnitudes was not completely efficient, according to the tests. However, since we monitored more than 120000 objects every night a less general treatment was not feasible.

Some general criteria were adopted to evaluate whether the frame and final reduction had sufficient quality so as not to cause systematic effects in the analysis and search for variable stars in the databases, like spurious alarms of variability.

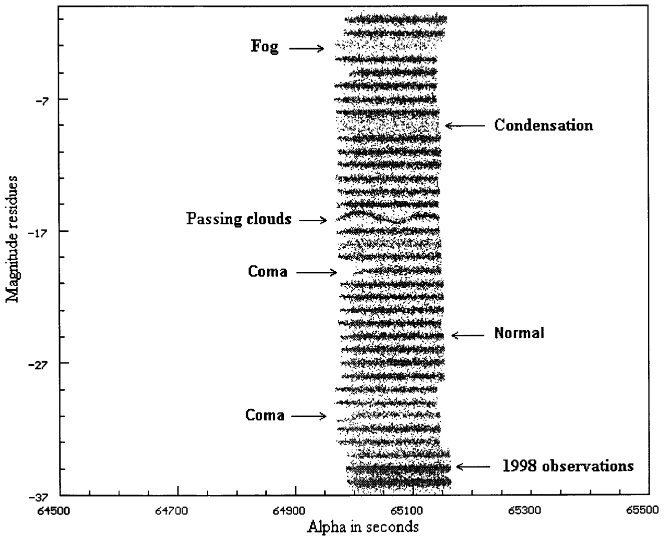

Fig. 3. Residues of the magnitude in function of the sidereal time. Each row represents a single night of observation. Several effects that provoke the frame elimination are indicated in the figure. It is possible to note the increase of the number of monitored objects in the 1998 campaign

The first of these criteria is the comparison of the quadratic sum of the differences between the night and the mean values. Whenever these differences were ≥ 0.1 in magnitude, the frame was eliminated. Analogously, the results in right ascension and declination were inspected to check whether the behavior of the residues (the difference between the night and the mean values) of the magnitude as a function of the sidereal time was abnormal. Figure 3 shows this behavior for LI window, note that problematic nights and the identification of the night effects are clearly visible in the plot and caused the elimination of unsuitable data.

5. Searching for variable stars

To organize and analyze such an amount of data is not a trivial work, especially if the final goal is to investigate the presence of variable objects in the monitored regions in real time.

A program called *Class32* was developed by us to handle the huge volume of data. Basically the program constructs a database for each investigated window, where a main table contains mean information about all objects already detected, and an individual record for each object as well. In the main table we record

- A sequential numerical identification;
- The mean value of the right ascension;
- The mean value of the declination;
- The standard deviations corresponding to right ascension and declination;

- The mean differential magnitude;
- Standard deviation of the mean differential magnitude;
- The number of times that the object was detected;
- A Flag that indicates the confidence of the identification;
- Gregorian date of the last observation;
- A second flag (hereafter, AlarmFlag) that warns if the object suffered light variations and in how many days.

The individual table for each object contains (for each night):

- Gregorian observation date;
- The calculated right ascension;
- The calculated declination;
- Differential magnitude with respect to the reference set;
- The magnitude error;
- The AlarmFlag;
- Apparent magnitude;
- Julian Date of the observation.

Now, we will describe in more detail the contents of the tables. The inputs of this program are the positions values (right ascension in hours, declination in degrees), differential magnitude, magnitude, the respective errors and the Julian Date. For a given night, the input positions of the detected stars are compared with the mean values available in the main table. The first criterion for identification is that the centroid falls within the same pixel.

The second criterion, useful for the confirmation of the identification is

$$\bar{x} + \mathrm{d}\bar{x} > x - \mathrm{d}x \tag{2}$$

$$\bar{x} - \mathrm{d}\bar{x} > x + \mathrm{d}x \tag{3}$$

for the right ascension and declination, where $\bar{x}$ and $\mathrm{d}\bar{x}$ indicate the mean value and its error and x and $\mathrm{d}x$ are the night values. The criterion of Eqs. (2, 3) verifies if the last measurement, allowing for the error, is inside the region delimited by the mean value, calculated from the previous nights, plus one standard deviation.

After the identification, the program makes a series of hierarchical tests to verify if the object presents light variations. The first test is somewhat arbitrary and connected with the variations that we consider easily measurable by our project

$$|\bar{m} - m| > 0.3 \tag{4}$$

where $\bar{m}$ is the mean differential magnitude.

The next test, which is applied only if the star satisfies Eq. (4), is more refined and compares the night measurement with the mean value, taking into account the standard deviation of the mean differential magnitude ($\mathrm{d}\bar{m}$)

$$m > \bar{m} + n\mathrm{d}\bar{m} \tag{5}$$

$$m < \bar{m} - n\mathrm{d}\bar{m} \tag{6}$$

where $n = 3$ was adopted after extensive testing of the method.

The last test, which is applied only if the star passed through the tests of Eqs. (5, 6), takes into account the "instantaneous" error of that particular night and reads

$$|m - \bar{m}| < |\mathrm{d}m| + |\mathrm{d}\bar{m}| \,. \tag{7}$$

Even if the star satisfies the criterion of Eq. (4) only, the program registers an alarm (the AlarmFlag). Our experience shows that stars passing only in the first criteria are those near the detection limit and have large photometric errors. Most of the stars that show a real (and reliable) variable behavior have passed through all criteria.

As a test of the performance of the *Class32* program and with the aim of verifying our actual observational capabilities, we have observed the microlensing event 97-BLG-56, detected by the MACHO group, as a target-of-opportunity. Since the star was known to vary and other groups were monitoring it, a comparison and evaluation of the actual behavior of the devised variability criteria was possible in a quite accurate form. We obtained 16 good quality frames of the event. The reduction was made of the standard way but, since the field does not belong to any of the monitored fields, we had to calculate the differential magnitude with respect to the available Tycho stars in the same field, subtracting the stars brighter than $m_{\mathrm{Val}} = 8.5$ and those having a Tycho quality index worse than 5 (see Paper I).

The identification of the ongoing event in the database was successful and the program gave the expected alarm in 11 consecutive nights. The light curve of the event can be seen in Fig. 4, where our data was superimposed to the OGLE I filter measurements (Udalski et al. 1997). Our data, and the subsequent analysis of the 97-BLG-56 will be the subject of a future paper.

Real time processing of the data, though being the ultimate goal of the programme, was not indeed possible in this first stage of the project. The *Class32* is still under development and presently the time it takes for a full processing of one night is greater than expected. We will discuss the future modifications in our analysis methods in the last section.

6. Variable stars analysis: The minimum entropy method

Because of poor weather conditions and unexpected instrumental problems the 1998 campaign was finished slightly earlier than planned in August 1998. The final number of observations including both campaigns was less than originally expected: a total of 76 good quality nights with an average of 35 observations per window. Even if the data is good enough for the discovery of variables, this has limited our analysis of the variables found (see below).

When we finished all the analysis with the *Class32* program, we had finally obtained data from 124976 objects in the 12 databases. The AlarmFlag of each object was

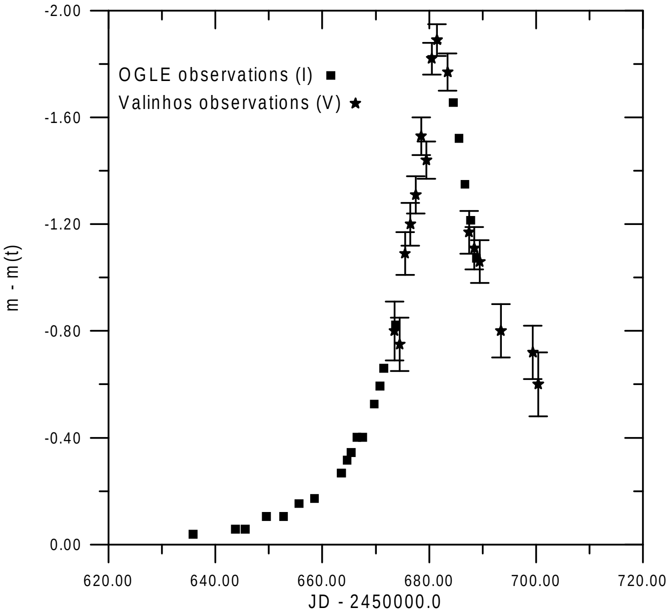

Fig. 4. Comparison between our observations (in $V_{\rm Val}$ filter) and OGLE data (I filter, taken from Udalski et al. 1997). The axes indicate the difference between the stationary value of the magnitude (m) and the night measure during the amplification ($m(t)$), versus the Julian Date

Table 5. The final number of objects and variable stars found in each window

Window	n° of stars	n° of variables
BE	14750	74
BG	10114	54
BJ	5941	15
LA	12952	79
LB	10535	33
LC	12466	32
LD	10628	35
LI	9006	32
LR	11820	56
LT	8454	23
LU	8630	20
LV	9680	26
Total	124976	479

checked and the stars that presented a significant variation (sufficient number of observations, reasonable photometric errors, large magnitude variations, etc.) selected. The total number of objects per window and number of variables found are in Table 5.

Among the variables we have found (see the complete listings in Appendix B), a major subset shows hints of periodic variations. However, if we do not have clear evidence to say that the star is periodic, its classification is highly compromised. As stressed before, the main problem is that we do not have as yet chromatic/spectral information about the objects. Since the variable classes are defined mainly by the spectral characteristics (especially in the case of aperiodic variable stars), the study of the individual stars given in the Appendix B is a natural and necessary next step. It should be remarked that the temporal covering of our data is not (generally speaking) broad enough to affirm whether a given star that does not show periodic variations is actually aperiodic.

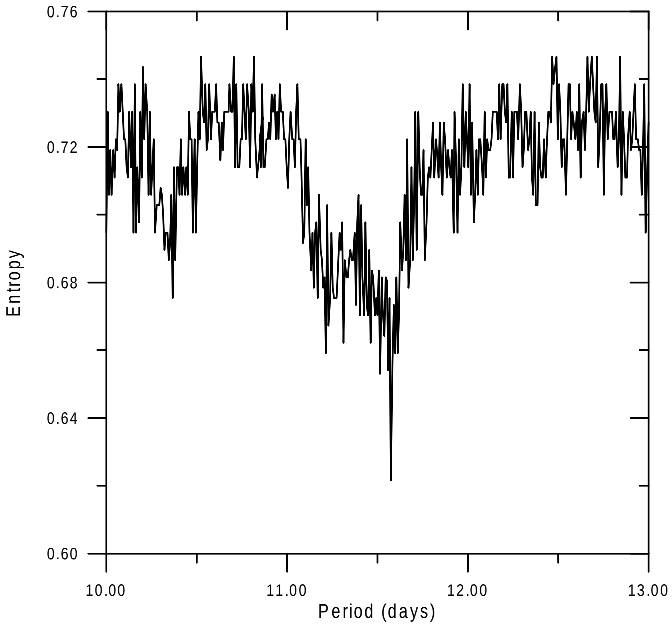

Fig. 5. S vs. p_j diagram for the star LI471, a known W Virginis

In the case of the stars with hints of periodic light curves it is important to estimate the period (or periods) for a tentative classification. Several algorithms to perform period calculation exist, of which the Fourier method is the most popular. However, as is well-known, the Fourier method works with equally-spaced points from a temporal series, which is never the case for astronomical measures. Many authors (see, for example, Cuypers 1987) have developed a modified Fourier analysis for non-equally-spaced points. These works have generally resulted in computational time-consuming algorithms. In our analysis we have adopted a new method (the minimum entrophy method), developed by Cincotta et al. (1995).

This method is based on the minimization of the information entropy for the true period(s). The rigorous mathematical formulation can be found in Cincotta et al. (1996), for example. We will briefly describe the method.

Consider a temporal series ($u(t_i)$) and the set of periods to test p_j ($j = 1, ..., n$). According to Cincotta et al. (1995) we have calculated the phase of the temporal series and created a unitary (normalized) plane (ϕ, u), where ϕ is the phase. For each trial period p_j, the light curve has been constructed and distributed in (ϕ, u) plane, that is divided in an arbitrary number (N) of partitions. The next step was to calculate the probability (μ_i) for a point to fall in one partition, dividing the number of points in each

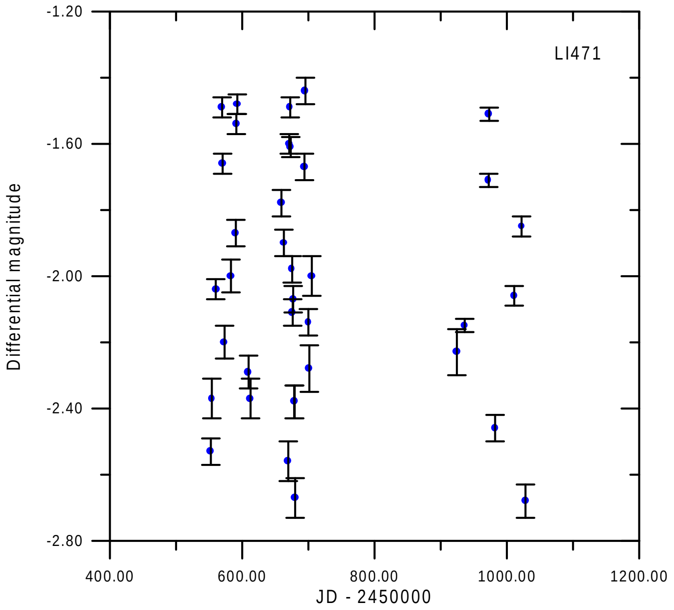

Fig. 6. Light curve of the star LI471

partition by the total number of points in the temporal series. Finally we have computed the entropy as

$$S = -\sum_{i=1}^{N} \mu_i \ln(\mu_i) \tag{8}$$

If the trial period is not the real one, the light curve points will be uniformly distributed in the plane (ϕ, u) and the entropy will be maximum. On the other hand, if the trial period matches is the actual period, the points will be limited to a small region of the plane and we will have a minimum of the entropy. Therefore, we expect that minima in the S vs. p_j diagram correspond to the actual period(s).

The method works very well when the light curve is sufficiently sampled (empirically, ≥ 50 points for the period determination to be strictly independent of the partition number (N)). This is not quite the case of our databases, although the actual number of points is not too low in some cases. Thus, the application of the method remains feasible, but noisier S vs. p_j diagrams are obtained. On the other hand, the computing processing time is less time-consuming than the modified Fourier analysis and, in principle, we believed suitable for our extensive databases (see discussion below). Another well-known problem is the presence of the harmonics, which can cause some confusion when we have few points.

Simulations and comparisons between minimum entropy and modified Fourier analysis were performed by Cincotta et al. (1995). Their tests showed that the minimum entropy method is more efficient for the resolution of multiple periods than the Fourier analysis. However, the accuracy of the estimated periods are not known yet and we intend to collaborate with the development of the method with its massive application to our databases. A comparison between several methods to determine periods present in our data will be the subject of a future study.

For simplicity, we consider that the stars have only one period. We shall present some examples from our databases to see how this works and evaluate the results. As we say before, the method is independent of the partition number when the series is well sampled, this isn't our case and, for each star, the calculations were done for several configurations of parameters, varying the number of partition (N) and trial period interval. We considered a period as found when the minimum persisted for all tried configuration (the differences between minima in each configuration are in the less significative digits).

The star LI471 is a W Virginis previously identified, and belonging to GCVS (General Catalogue of Variable Stars, Khopolov et al. 1988), with an attributed 11.49 days period. The light curve of the star (with our data) can be seen in Fig. 6. Figure 5 shows the S vs. p_j diagram for that star which is noisy as expected. Nevertheless, the minimum we have obtained by applying the minimum entropy method is 11.50 days, consistent with the catalogued value. This example shows that, in spite of the noise, accurate determinations are possible in an efficient form.

Besides the problem of the scarcity of the points, our photometric errors are quite large, which in turn provokes more noise in the diagrams. As a result of the analysis we have checked that the determination of small periods is easier and more reliable than the determination of large periods (like Miras). This fact is closely related to the definition of the phase (see Cincotta et al. 1995) which is inversely proportional to the period. To give an example, we discuss the star LA1552, not known before and preliminary classified as a Mira, which reflects this difficulty very well (the light curve can be seen is Fig. 9). Figure 7 shows the S vs. p_j diagram. We estimate the period in 323.2 days, but in this case the method is more dependent on the number the partitions.

As a further example of the capability of the method to find periods smaller than 1 day, we show the case of BJ878, a RR Lyrae star already known and belonging to GCVS (Fig. 10). The catalogued period is 0.37 days and our best estimation was 0.33 days. Figure 8 shows the S vs. p_j diagram, with a well resolved minimum. In fact, it is not impossible that the catalogued period has to be corrected if further studies confirm the present value.

Even in cases where periodicity is suggested by the data, we have not been able to determine period for all those candidate stars. Some of them have so few points that it was impossible to draw a reliable conclusion. These stars are indicated with "NC" (not calculated) in the nineth column in the catalogue presented in Appendix B. The stars that we believe to be periodic, but for which a period could not be reliably found, are indicated with "NF" (not found) in the same column.

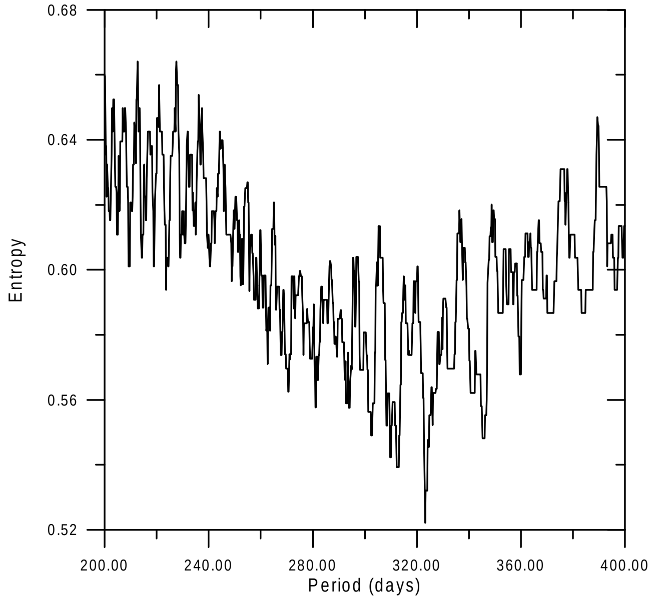

Fig. 7. S vs. p_j diagram for the star LA1552, classified as a Mira. The estimated period is 323.2 days

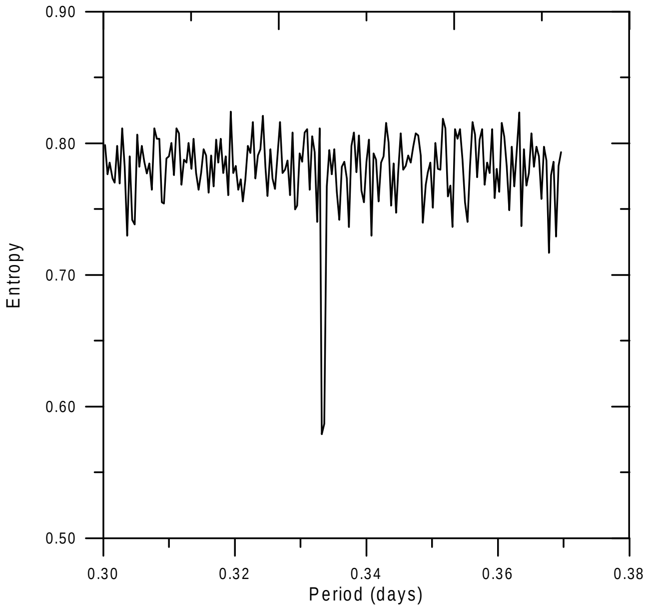

Fig. 8. S vs. p_j diagram for the star BJ878, a RR Lyrae. The estimated period was 0.33 days

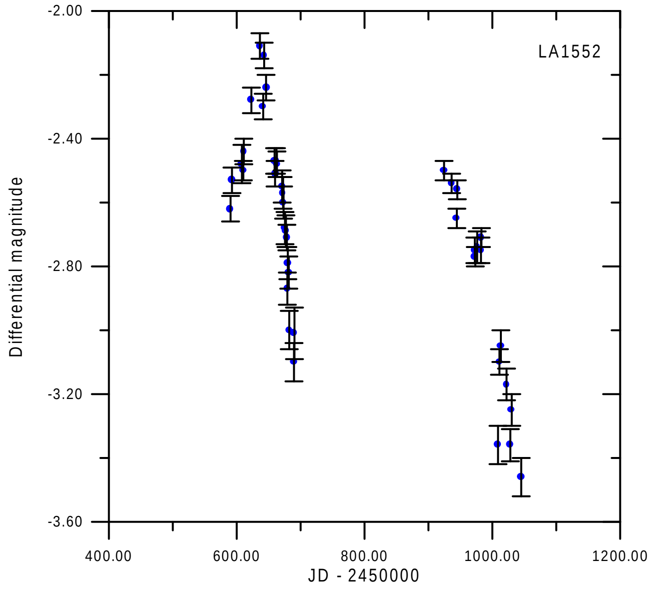

Fig. 9. Light curve of the star LA1552

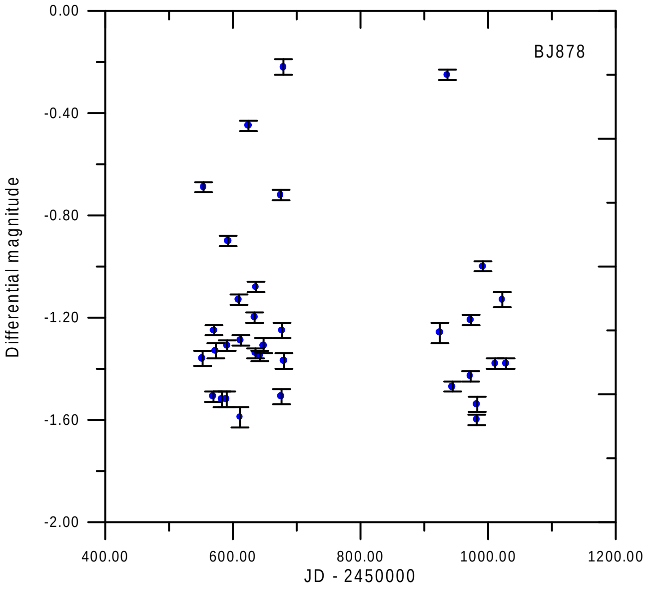

Fig. 10. Light curve of the star BJ878

To perform a preliminary variable star classification, we have based our judgement on:

- The available periods as calculated with the minimum entropy method;
- The observed amplitude of variations;
- The shape of light curves, which have been compared to the observed for variables already existing in the GCVS;
- The variable classes that we expected a priori among the monitored stars, as described in the Introduction.

All stars positions were compared with the ones of the variable objects belonging to the GCVS and NSV (New Suspected Variables, Kukarkin et al. 1982) catalogues and to those of the SIMBAD database using WWW interface. Among the 479 stars that showed significant light variations found in our database, only 16 were already present in other catalogues (including the IRAS catalog

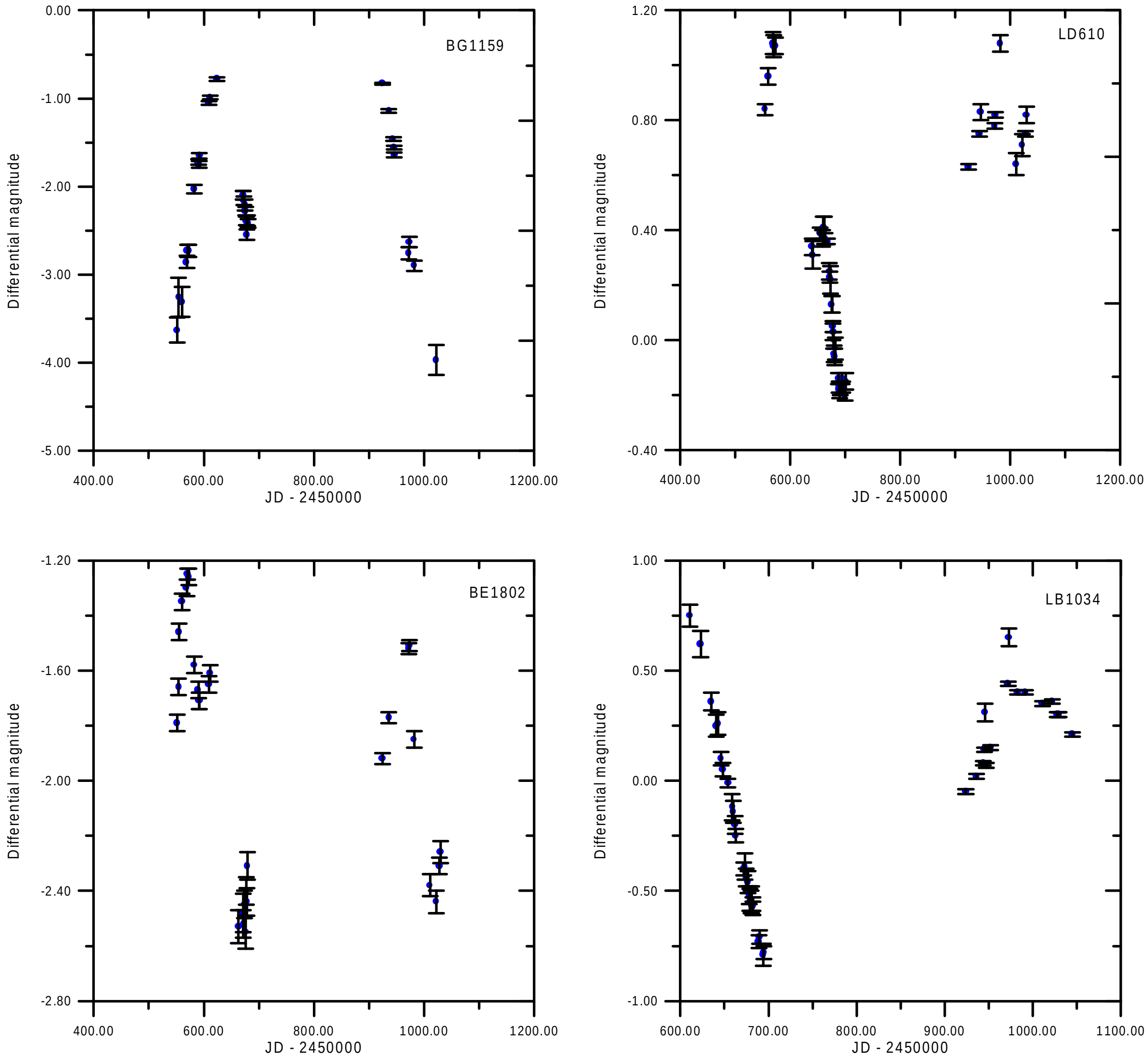

Fig. 11. Light curves of the stars BG1159, LD610, BE1802 and LB1034

(Beichman et al. 1988), the work of Hazen (1996) on the variables in NGC 6558 (in the center of BE window), the CCDM (Catalog of Double and Multiple stars) by Dommange (1983), besides the quoted GCVS and NSV catalogues). Therefore, 96.7% of the variables in the new databases were unknown until now.

Considering our limitations, we restricted the classification of our variables to four broad classes *defined* as:

- Mira-type variables: stars with period greater than 80 days, amplitude of the variation greater than 2.5 magnitudes (approximately), and light curves alike BG1159 (Fig. 11, Appendix A), a Mira already present in GCVS;
- Semi-regular-type variables: stars with periods greater than 80 days and light curves alike the Miras, but with amplitude variation smaller than 2.5 magnitudes;
- Cepheid-type variables: stars with periods between 1 and 50 days, (approximately), and mean amplitude variations of 0.9 magnitudes. The differentiation between classical cepheids, that populate the galactic discs, and W Virginis (or type II cepheids), that are present among the older population (halo, bulge), is possible only with the knowledge of morphological differences in their light curves. Since we are not sensitive to these details, we have classified these stars as "cepheids" without attempting a finer discrimination;
- RR Lyrae-type variables: stars with periods between 0.2 and 1 day and light variations of about 1 magnitude. Among the known sub-types RRc stars have periods between 0.2 and 0.5 days and amplitude of 0.5 magnitudes. Their light curves have senoidal shapes. The RRab have periods between 0.4 and 1 day, with amplitudes up to 1 magnitude, and their light curves are asymmetric. Again, we are not sensitive to shape details of the light curves and thus labeled these stars generically as "RR Lyrae".

The result of this analysis can be appreciated in the tenth column of the tables in Appendix B, which

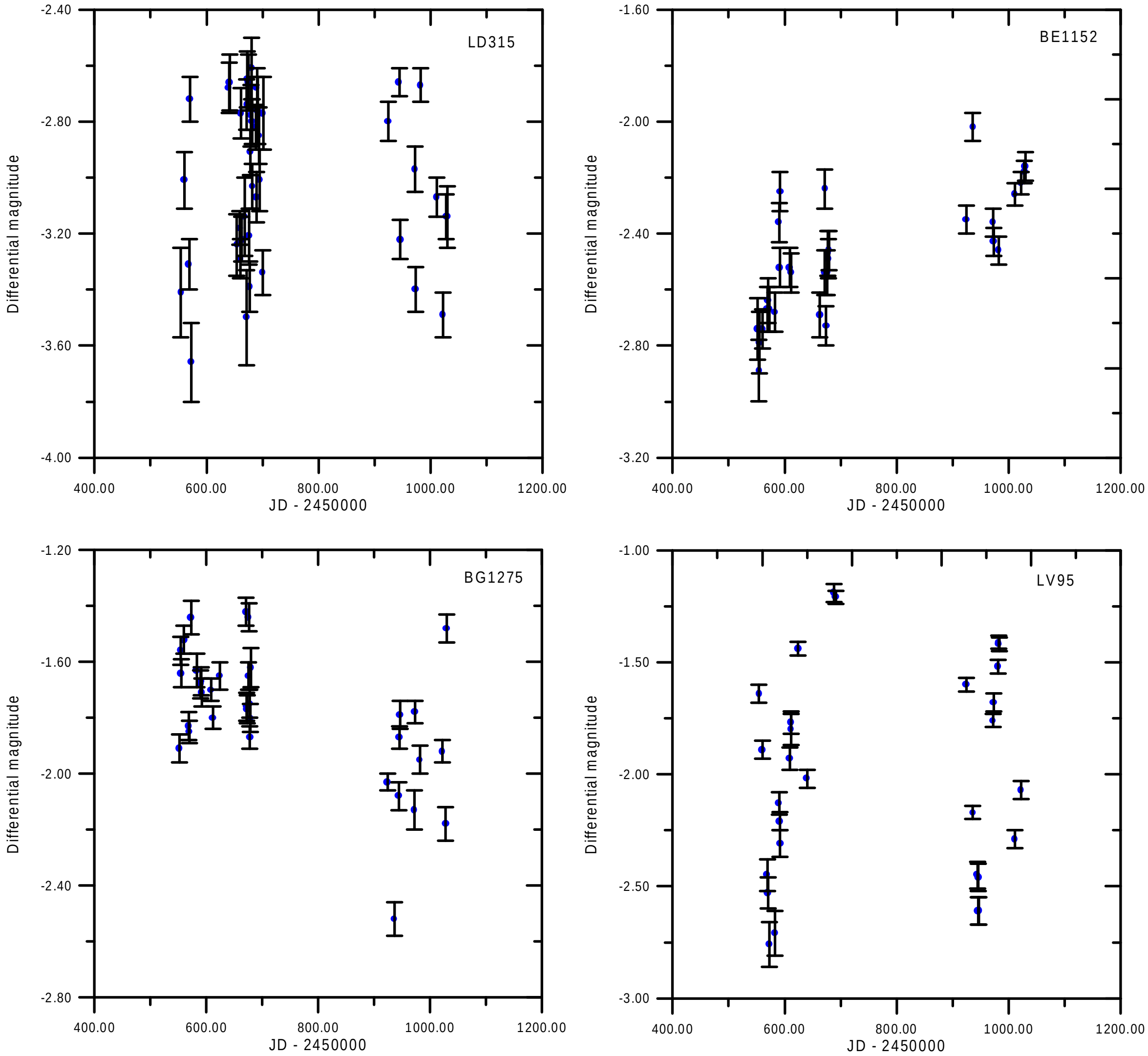

Fig. 12. Light curves of the stars LD315, BE1152, BG1275 and LV95

constitutes our very preliminary classification of the variable stars and serves as a starting point for more comprehensive studies of these objects.

7. Conclusions and future perspectives

The development of a photometric survey with the Valinhos CCD Meridian Circle has permitted the identification of a significative number of previously unknown variables inside selected low-extinction windows towards the galactic bulge. Even if limited, the instrument could be used everyday and has a relatively simple reduction data procedure, features that are clearly desirable for massive searches like ours. Other observational programmes with the aim of detecting magnitude variations were also implemented like the monitoring of extragalactic sources brighter than $m_{\rm Val} = 16$ (Teixeira et al. 1998).

The use of Meridian Circle has other advantages: we were able to provide excellent positions for $\sim$ 30000 stars (both variables and non-variables) among the 120000 in the database, which are in most cases comparable to the secondary catalog precisions (Table 2). This is a useful result for astrometric works, where a dense catalog of references is generally needed without any requirement of photometric stability. Proper motions researches, that are very important for the understanding of galactic kinematics are now possible and we plan to contribute with more than 2000 frames of the windows (including those without high photometric quality but good enough for astrometric purposes) stored in CD ROM.

The *Class32* program, that was developed to organize the data and search for variable objects, is simple and can be further improved. The main problem we found is the time of processing that made it until now impossible a real-time analysis, although we are working on an updated version of the program for the implementation of the project in a larger and more versatile instrument (likely a robotic 40 cm telescope). Some obvious modifications will

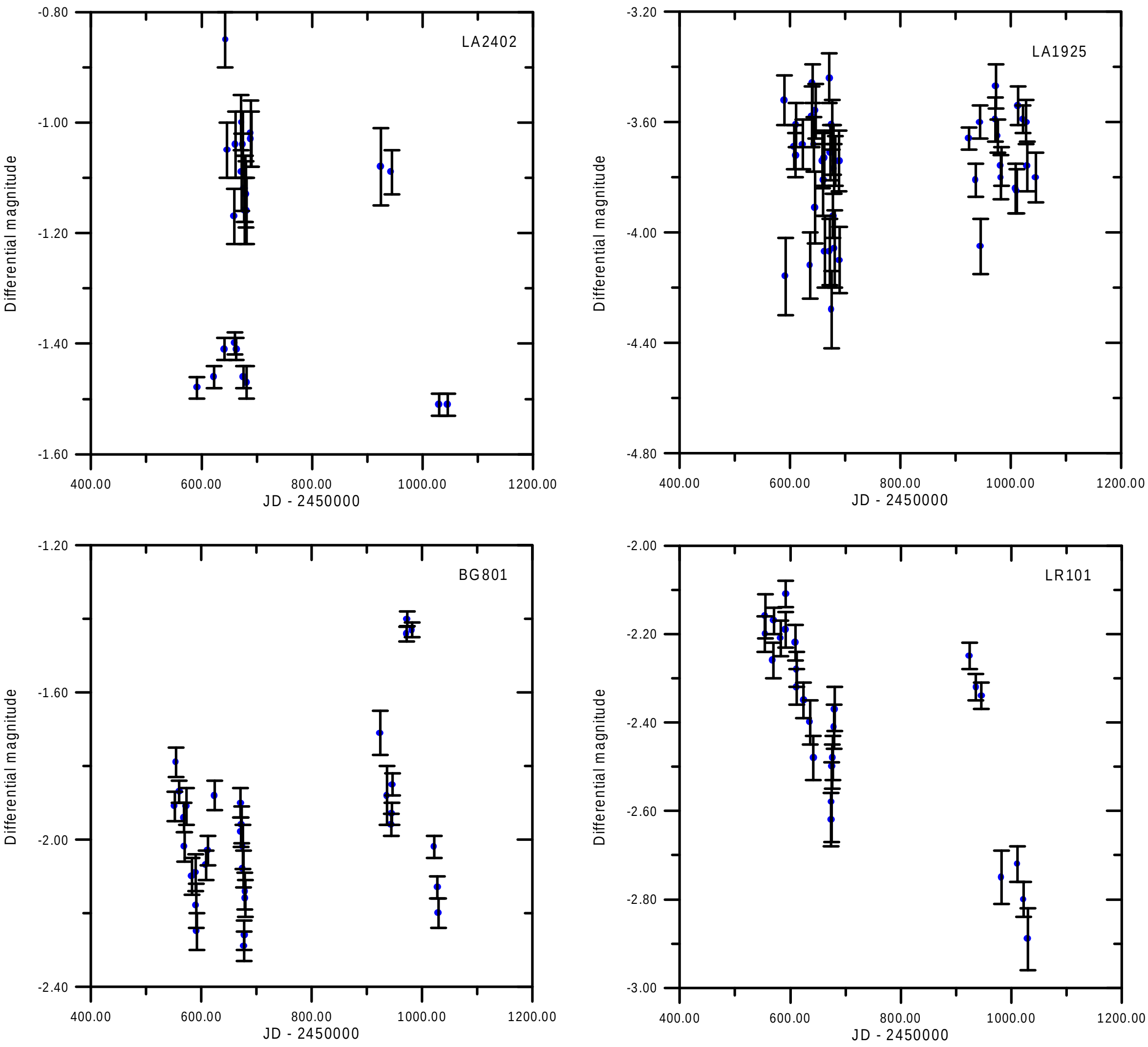

Fig. 13. Light curves of the stars LA2402, LA1925, BG801 and LR101

be needed, for example: the first criterion of identification is strong and possible only because we were working with an astrometric instrument. The system of alarms and flags proved to be efficient and most of the spurious alerts were in fact caused by the objects that are near the detection limit and had large photometric errors to be considered.

After all the reduction process and analysis, we found 479 variable stars with light variations greater than 0.3 magnitudes (the databases are continually reprocessed and studied to complete and enlarge the catalogue). Except for a small number of cases (like the Miras) the classification is tentative since we do not have spectral information as yet and our databases have small temporal coverage. The final number of points on the light curve is smaller than originally expected and, in addition to the large photometric errors and the fact that an initial estimate of the range for period is unknown, its calculation was compromised. In spite of these limitations, we were able to find period estimations for 79 variables (16.49% of the selected stars) using the minimum entropy method (Cincotta et al. 1995). We intend to use, in a future work, other methods (like PDM and modified Fourier method) to optimize the results for our extreme conditions of large errors and few points.

In some light curves it was observed that the photometric errors are larger for the brightest points (see the light curve of the star LA2402 (Fig. 13, Appendix A) for an example). We believe that this is caused by the effect of chromatic aberration in the meridian circle, as briefly described in Appendix C. The emission of these stars would be dominated by higher wavelengths and the flux distribution would be wider and drops faster. This would provoke an increase in the flux error determination by the Gaussian fit. Consequently, the magnitude errors should also increase.

Thus, 97 variables were classified, among them, 21 Miras, 71 stars classified as cepheids, 2 as RR Lyrae, 1 as an eclipsing binary and 3 as semi-regulars. Note

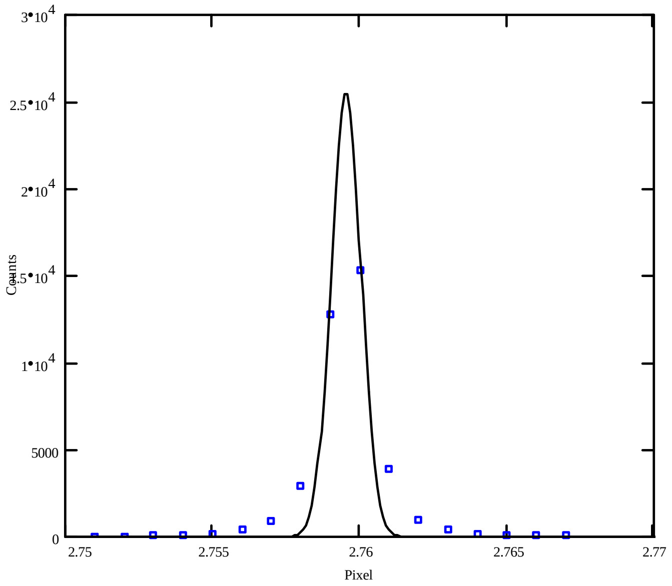

Fig. 14. A tentative Gaussian fit to the observed image profile

that from our light curves, stars with periods smaller than 1 day and until 50 days, approximately, have the same shape because our temporal resolution and the few points obtained. Among the stars classified as “cepheids” many binaries probably occur. This should be the case of RR Lyrae too, but a more accurate classification was not possible without spectral information. The star classified like eclipsing binary is already known from the GCVS.

We hope to refine this classification in future studies and contribute to other ongoing investigations involving these stars.

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Appendix A: Light curves examples

The following figures are representative of the light curves of the 479 variable stars discovery and/or observed by the project. It is important to remember that since we worked with differential magnitudes, the graphics do not display the apparent magnitudes. Of course, the mean values of the magnitudes of reference stars vary between nights. Table A1 can be used for reference information about the apparent magnitude of the stars ($m_{\rm Val}$). The remaining light curves (not shown here), can be obtained electronically from the authors upon request.

Table A1. Mean magnitude of the reference stars for each window that can be used to estimate the apparent magnitudes in light curves

Window	Mean magnitude ($m_{\rm Val}$)
BE	11.888
BG	11.891
BJ	11.804
LA	11.619
LB	11.626
LC	11.513
LD	11.591
LI	11.961
LR	11.612
LT	11.627
LU	11.685
LV	12.052

Appendix B: Valinhos variable stars catalogues

The Tables B.1 to B.12 contain the catalogue of variable stars discovered and/or observed for the 12 low-extinction fields towards the galactic bulge.

The first column of the catalog indicates the star label, formed by a name that identifies the window (see Table 1) and a sequential counter that indicates the position of the object in the corresponding database. The following columns display successively the mean right ascension, the mean declination, their standard deviations (in seconds and in arcseconds, respectively) (J2000); the mean magnitude observed ($m_{\rm Val}$), the difference between the maximum and the minimum magnitude value observed, the number of observations, a estimation for the period, if possible, or an indication “NF” when the stars show periodic characteristics but we are not able to find a period, or “NC” when the star can be aperiodic or have few observations. The next column gives the tentative classification and the last are the remarks about the previous known variables.

Complete databases up to $m_{\rm Val} = 16$ or better, with all monitored stars will be available soon and will be published elsewhere. Finding charts will be available upon request from the authors.

Appendix C: Distortion of the image profile by the chromatic aberration in refractor instruments

An interesting property of the Meridian Circle was noted and studied by us since the beginning of the programme in a parallel work. It is well-known that the image profile of refractor instruments, like the Valinhos Meridian Circle, suffers distortions because of the objective chromatic aberration. This effect provokes that, in the focal plane of the instrument (in which the CCD is placed), a *composition* of several Gaussians (which are the intersections of the flux distribution formed at higher wavelengths) is actually observed. We display in Fig. 14 an observed flux distribution and a tentative pure Gaussian fit. As expected, the Gaussian does not fit the "wings" of the profile well since there is a non-negligible contribution from wavelengths other than the one for which focus is made.

Thus, the image profile reflects to a large extent intrinsic properties of the observed objects as modulated by the optical system. We are working to simulate the true (observed) profiles and expect some correlation between the profile shape and spectral type. This can be a future tool to obtain quick spectral information in the single-filter observations of the Meridian Circle, limited to the brightest stars that are better sampled.

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