

Large Scale Surveys: Present and Future

Current Status of the Microlensing Surveys

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Abstract. The ongoing microlensing searches have generated more photometric measurements of pulsating stars than all previous observing projects combined. In particular, OGLE has made $\sim 340,000$ B , V , and I -band measurements of $\sim 1,300$ Cepheids in the Large Magellanic Clouds accessible over Internet. Microlensing searches contributed to the development of very efficient image subtraction software which works best in crowded fields. This suggests the use of a period – flux amplitude rather than period – luminosity relation for the Cepheids for distance determination, as the flux amplitude is directly measurable with the image subtraction, and it is not biased by crowding. Future projects will dramatically increase the data rate, will provide all-sky coverage and a complete census of variables, including pulsating stars, to the ever fainter limits. Time will show which approach, a small number of large teams or a large number of small teams, will be more productive.

1. Introduction

Three groups: EROS, MACHO and OGLE, reported the detection of their first gravitational microlensing events in September of 1993 (Aubourg et al. 1993, Alcock et al. 1993, Udalski et al. 1993). By now several hundred microlensing events have been discovered, most of them towards the galactic bulge, some towards the Magellanic Clouds, and a few in other directions. The events are detected in real time, and are reported on the World Wide Web at the rate of approximately two per week. A mini-collaboration, DUO, reported the detection of 13 microlensing events (Alard & Guibert 1997), one of them due to a double lens (Alard, Mao, & Guibert 1995). The microlensing projects monitor tens of millions of stars, they have discovered over one hundred thousand variables, and over ten thousand pulsating stars. Information may be found at the Web sites:

OGLE, Poland: <http://www.astro.uw.edu.pl/~ftp/ogle>

OGLE, USA: <http://www.astro.princeton.edu/~ogle>

MACHO: <http://www.macho.mcmaster.ca/>

EROS: <http://www.lal.in2p3.fr/recherche/eros/>

Several new groups joined the search for, as well as the follow-up of the microlensing events. Their Web sites are:

MEGA: <http://www.astro.columbia.edu/~arlin/MEGA>
 MOA: <http://www.phys.vuw.ac.nz/dept/projects/moa/>
 AGAPE: <http://cdfinfo.in2p3.fr/Experiences/AGAPE/>
 PLANET: <http://www.astro.rug.nl/~planet/>

In addition, several other projects generate a huge volume of the photometric data. The following are the Web sites I was able to find:

DIRECT: <http://cfa-www.harvard.edu/~kstanek/DIRECT/>
 ROTSE: <http://rotsei.lanl.gov/>
 ROTSE:
http://umaxp1.physics.lsa.umich.edu/~mckay/rsv1/rsv1_home.htm
 LOTIS: <http://hubcap.clemson.edu/~ggwilli/LOTIS/>
 ASAS: <http://www.astro.uw.edu.pl/~gp/html/asas/asas.html>
 Ystar: <http://csaweb.yonsei.ac.kr/~byun/Ystar/>
 STARE:
http://www.hao.ucar.edu:80/public/research/stare/stare_synop.html

I expect to update the list as new projects come along, and they can be found on my home page at: <http://www.astro.princeton.edu/faculty/bp.html>.

In this paper some results obtained with the data generated by the microlensing projects are described. As I am not actively working on pulsating stars the choice is subjective, and some important findings may be missing. I apologize for the omissions. Fortunately, there will be many presentations at this conference by the representatives of most groups. Also, many important results may be found at the IAP conference: "Variable Stars and the Astrophysical Returns of the Microlensing Searches" in Paris in 1996 (cf. Ferlet et al. 1997). The likely prospects for the future of large scale automated surveys is also described in this paper.

2. Some Results Related to Pulsating Stars

There have been many papers about pulsating stars by the EROS and MACHO teams (Alcock et al. 1995, 1996, 1997a,b, 1998, 1999a, Bauer et al. 1999, Beaulieu et al. 1997a,b, Sasselov et al. 1997). The single most spectacular result was the period - luminosity ($P-L$) diagram for pulsating stars in the Large Magellanic Cloud by the MACHO collaboration. For the first time the two sequences of Cepheids: those pulsating in the fundamental mode and those pulsating in the first overtone were very clearly separated. In addition, several distinct $P-L$ sequences for red giants were also seen for the first time in the MACHO diagram. I trust it will be presented later at this conference.

Another spectacular result was obtained by the DUO collaboration, at the time a single graduate student, Christophe Alard. Using several hundred Schmidt camera plates from ESO covering a $5^\circ \times 5^\circ$ square in the sky near the galactic bulge, Alard (1996) discovered $\sim 15,000$ periodic variables and selected $\sim 1,500$ RRab stars. Using two photometric bands he constructed a reddening-independent histogram of their distance moduli. Two peaks appeared in the distribution: one corresponding to the distance of ~ 8 kpc, the second to the

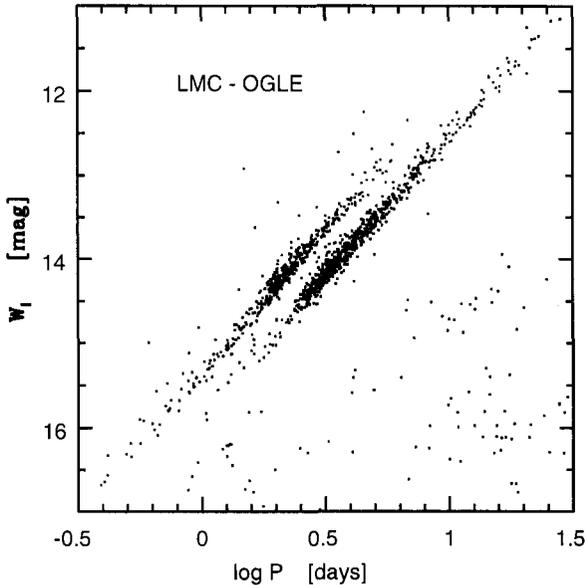


Figure 1. Period – luminosity relation for the LMC Cepheids based on public domain OGLE data (Udalski et al. 1999d). The lower and the upper sequences are populated by Cepheids pulsating in the fundamental mode and in the first overtone, respectively. The reddening independent quantity W_I is defined with the eq. (1).

distance of ~ 24 kpc, i.e. to the galactic bulge and to the Sagittarius dwarf galaxy, respectively. The RR Lyrae variables turned out to be excellent tracers of the extent of that recently discovered galaxy, extending its size well beyond the initial estimate (Ibata, Gilmore, & Irwin 1995).

Somewhat less spectacular, but very useful, was the photometry of over 200 RR Lyrae variables in the Sculptor dwarf galaxy by the OGLE collaboration (Kaluzny et al. 1995). This was promptly used by Kovács & Jurcsik (1996) to establish a very good correlation between the shape of the RR Lyrae light curves and the absolute magnitudes.

The recent series of OGLE papers on Cepheids in the Magellanic Clouds (Udalski et al. 1999a,b,c,d) made a catalog of $\sim 1,300$ Cepheids in the LMC, and a total of $\sim 340,000$ photometric measurements in standard I , V , and B -bands, accessible over the Internet (Udalski et al. 1999d). Note, that just several months ago a paper was posted on astro-ph (Lanoix et al. 1999) presenting “an exhaustive compilation of all published data of extragalactic Cepheids”. The total number of measurements in the compilation was about 3,000, i.e. two orders of magnitude fewer than in the paper by Udalski et al. (1999d).

The $P-L$ relation for the LMC Cepheids based on the OGLE public domain data is shown in Fig. 1. The magnitude W_I is the interstellar reddening-independent combination of I -band and V -band photometry:

$$W_I \equiv I - 1.55(V - I) \quad (1)$$

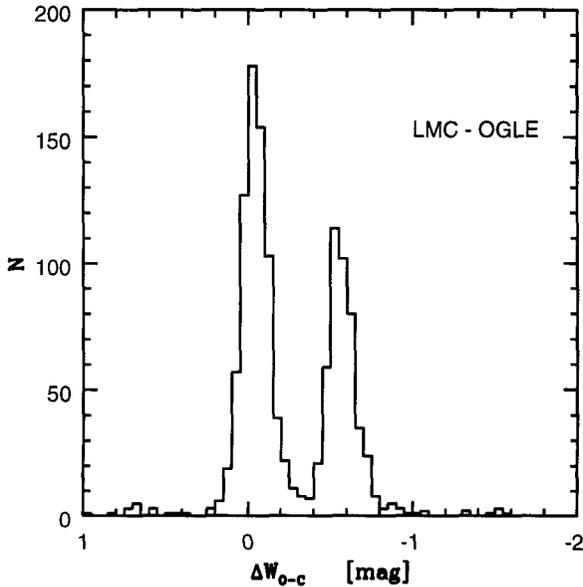


Figure 2. The luminosity function of the LMC Cepheids is shown with respect to the linear $P-L$ relation given with the eq. (2). The two peaks correspond to the fundamental mode (left) and the first overtone (right) pulsators. The definition of the magnitude difference ΔW_{O-C} is given with the eq. (2).

All these refer to the intensity-averaged mean magnitudes.

For each Cepheid a difference ΔW_{O-C} can be calculated between the actual value of W_I and the line fitted to the fundamental mode pulsators, given by Udalski et al. (1999c, Table 1) as

$$W_{I,C} = -3.277 \log P + 15.815 \quad , \quad \Delta W_{O-C} \equiv W_I - W_{I,C} \quad , \quad (2)$$

where P is the Cepheid period, in days. A histogram of the ΔW_I values is shown in Fig. 2. A very clear separation of the fundamental mode and the first overtone mode pulsators is apparent in both Figures.

3. Prospects for the Near Future

In my view the single most important outcome of the microlensing searches is the practical demonstration that it is feasible to monitor tens of millions of stars per night, making up to $\sim 10^{10}$ photometric measurements per year, using very modest instrumentation: a 1-m class telescope, a CCD camera, and several PC-class computers. There can be no doubt that this technology will develop into much larger surveys.

The fates of the current projects vary from case to case. The largest of them, MACHO, will suffer the ultimate Y2K problem: it will be terminated on December 31, 1999. As far as I know, EROS will continue till at least 2002, while

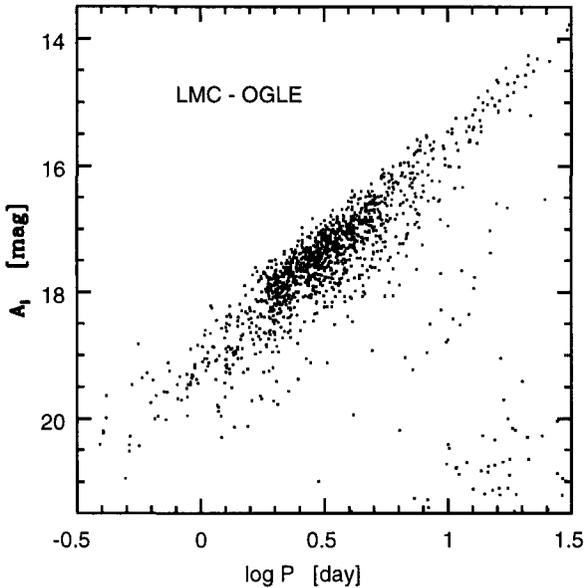


Figure 3. Period – flux amplitude relation for the LMC Cepheids based on public domain OGLE data (Udalski et al. 1999d). The flux magnitude in the I-band, A_I , is defined as the magnitude equivalent of the first term in the Fourier expansion; it is not a full amplitude.

there is no time limit for OGLE. Currently OGLE uses a single $2K \times 2K$ CCD camera in a drift scan mode (cf. Udalski, Szymański, & Kubiak 1997, OGLE-II) to monitor $\sim 30 \times 10^6$ stars per night. A new mosaic $8K \times 8K$ CCD camera will become operational in the year 2000, and it will be used in a still-frame mode. The data rate will increase by a factor ~ 10 , leading to the detection of ~ 500 microlensing events per year with the OGLE-III system.

While hardware upgrades are important, the same is true about software. The first attempt to use the image subtraction technique to search for gravitational microlensing was published by Tomaney & Crotts (1996). Preliminary application of image subtraction by the MACHO collaboration increased the number of detected microlensing events by a factor ~ 2 (Alcock et al. 1999b,c).

New, very powerful image subtraction software has been recently developed by Alard & Lupton (1997) using OGLE data. It has been applied to the old OGLE microlensing data, dramatically improving photometric accuracy (Alard 1999a). Olech et al. (1999) used it to detect RR Lyrae variables all the way to the center of a globular cluster M5 with ground-based CCD images. Woźniak et al. (1999) developed with it a real-time photometry system for Huchra's lens (2237+0305). A full data pipeline based on Alard & Lupton (1997) and Alard (1999b) software is currently under development by Woźniak (1999). The goal is to analyze all OGLE-II galactic bulge data. It is likely that incorporation of this software in the forthcoming OGLE-III system will result in a real-time detection rate of $\sim 1,000$ microlensing events per year.

Image subtraction generates blending-independent determination of stellar flux variations. This naturally leads to a period – flux amplitude ($P-A$) rather than to $P-L$ relation for Cepheids. Let the flux of radiation from a star and its full flux amplitude be defined for the I -band as

$$F_I \equiv 10^{-0.4I}, \quad \Delta F_I = F_{I,\max} - F_{I,\min}, \quad \Delta m_{F,I} \equiv -2.5 \log_{10}(\Delta F_I) \quad (3)$$

Note, that ΔF_I is the quantity measured using the image subtraction method, and $\Delta m_{F,I}$ is the same quantity expressed in magnitudes, which are the units preferred by astronomers. Also note, that both quantities: ΔF_I and $\Delta m_{F,I}$ are independent of blending, and can be reliably measured in the most crowded environments, without any bias. Unfortunately, the period – flux amplitude relation has significantly more scatter than the period – luminosity relation, as it is apparent in Fig. 3.

The blending of a Cepheid with images of nearby bright stars makes it appear brighter than it really is. Recently, Mochejska et al. (1999) and Stanek & Udalski (1999) pointed out that this may lead to a systematic underestimate of distance moduli of the most distant galaxies studied by the HST Key Project. We expect that a $P-A$ relation will eliminate this systematic error. However, it is not known if the $P-A$ relation is as universal as the $P-L$ relation appears to be.

The microlensing searches do not have a monopoly for generating huge sets of photometric measurements. DIRECT is a project searching for pulsating and eclipsing variables in nearby galaxies M31 and M33 (Kaluzny et al. 1998, 1999, Stanek et al. 1999). A large number of Cepheids discovered by this project will provide the first opportunity to verify the $P-A$ relation when combined with the OGLE results for the Magellanic Clouds.

Several large projects using very small instruments are searching for optical flashes which may accompany gamma-ray bursts (ROTSE: Akerlof et al. 1999; LOTIS: Williams et al. 1999). They cover all sky every night down to ~ 14 mag. The first spectacular result was obtained by the ROTSE collaboration on 1999 January 23: the detection of an optical flash brighter than 9 mag from the burst GRB 990123, which was at the redshift $z = 1.6$ (Akerlof et al. 1999). The archive of ROTSE is a gold mine for studies of many kinds of variable objects, including pulsating stars. In the 2000 or so square degrees analyzed so far by McKey and his collaborators ~ 2000 variables were found, ~ 1800 of them new (McKey 1999).

Another project, ASAS, is in its early stages of development (Pojmański 1997, 1998), but with the intent to cover the whole sky with nightly observations of all objects brighter than ~ 14 mag initially, and to go deeper with time. This project has real-time photometry implemented from the start, and it has already demonstrated that even among stars as bright as 11 – 12 mag, over 70% of all variables have not been cataloged, and they are waiting to be discovered.

4. Prospects for the Distant Future

There are many ideas about future expansion of sky monitoring, and many projects at various stages of implementation, planning or dreaming. The most ambitious of these is the idea of the Dark Matter Telescope (DMT), as proposed

by Angel et al. (1999) and by Armandroff et al. (1999). This dream is to built an 8.4-m telescope with a 3° field imaged at $f/1.25$, with the focal surface filled with 1.4×10^9 pixels in a very large mosaic CCD camera. The primary science objective is the determination of the distribution of dark matter in the universe by measuring weak gravitational lensing of galaxies over a large part of the sky. However, such an instrument could perform other spectacular tasks, as it could reach $V = 24$ mag in a 20-s exposure, and cover the whole sky to this depth in about 4 clear nights. While the hardware sounds very impressive, the software capable of handling in a meaningful way such a data rate may be even more challenging. Data access will not be easy either.

The DMT is an undertaking on such a huge scale that a research team even larger than the MACHO or EROS teams will be needed, first to obtain the necessary funds, next to implement the project, and finally to get science out of it. Does this imply that there will be no room for small teams in the astronomical future? I do not think so. With all its power a DMT-like instrument will be useless for the discovery of optical flashes like the one associated with the GRB 990123 (Akerlof et al. 1999). In order to detect such flashes independently of gamma-ray burst triggers a very different and far less expensive instrument is needed to continuously monitor all sky down to 14 mag, or so. Note that ROTSE and LOTIS cover ~ 400 square degrees in a single exposure with four telephoto lenses, each equipped with a $2K \times 2K$ CCD camera. To cover $\sim 10,000$ square degrees we need ~ 25 small systems like ROTSE or LOTIS. The likely cost of so many instruments would be in a relatively modest range $1 - 2 \times 10^6$ dollars. This level of funding is within reach of a small team. For example, the total hardware cost of the OGLE was $\sim 1.3 \times 10^6$ dollars.

The large membership of the MACHO and EROS teams created a misleading impression that this is the only way for the future. However, the current data rate of OGLE is within a factor 2 or so of the current data rate of MACHO, yet the OGLE team has only 7 members, most of them students. Next year the OGLE data rate will increase by a factor ~ 10 , with one or two more students joining the project. ASAS has only one senior person and one part-time student, yet within a year its data rate is likely to equal the current data rate from either ROTSE and LOTIS, and all data will be processed in real time. The most spectacular example of a capability of a small team has been demonstrated by DUO, with nearly all data analysis and writing of science papers done by just one graduate student, Christophe Alard.

Obviously, it is not possible for a small team to make full use of all the data. Hence, OGLE (and ASAS in future) makes its data public domain as soon as feasible. The bottleneck is quality control. However, once the data pipeline is fully debugged, it might be possible for the software to handle quality control nearly in real time. It might be possible to make most data public domain right away. Would this pose a threat to the scientific recognition of a small team? I do not think so. Whoever uses the data will have to give full credit to the source of the data. Also, members of a small team could prepare new software needed to take full advantage of any new hardware upgrades ahead of time, and this way have a head start over the competition. It is conceivable that the scientific recognition of a team making good data public domain could be strongly enhanced by the scientific results obtained with their data by others.

Several bottlenecks have to be overcome. The most difficult and expensive technical bottleneck is software, as has been learned by large projects like the Sloan Digital Sky Survey (SDSS) and the 2MASS. It has not been demonstrated yet that a truly large dataset can be made public domain at a reasonable cost. Perhaps even more difficult are psychological and sociological problems: will the authors of useful public domain data get enough recognition to be offered tenured positions at major universities? I think these are very important issues. Most of us enjoy working in small groups, and find it much less pleasant and less efficient to work almost anonymously in an industrial size mega-team. Also, managing large teams is very complicated and tedious, with huge overheads in time, funds, and loss of satisfaction. I think that whenever a project can be meaningfully broken down into a number of smaller parts it should be divided into such parts. It is much better to reference the work of separate but collaborating groups, rather than to have a paper with dozens of co-authors, with no clear division of responsibility and credit for various parts of the work. Time will tell if small or large teams will lead in scientific discoveries in the future.

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Discussion

Drahomir Chochol: Have you discovered any microlensing event binaries during the surveys?

Bohdan Paczynski: Yes, many microlensing events were found to be due to binary lenses. The total number of binary events detected so far is almost 30, compared with about 400 single events.

Michael Reed: Is an 8-m survey that can map the whole sky in four nights better (perhaps a replacement) than 14+ surveys that can only see small regions of the sky?

Bohdan Paczynski: The dreamed-about 8-m survey telescope can do better anything that current surveys do, but it cannot do everything, and cannot replace all existing or planned smaller surveys. In particular, if it is going to reach 24 mag, its detectors will saturate at 14 mag. There is a lot of interesting things happening at <14 mag, and those bright sources are much better for very accurate follow-up studies.