THE CONTRIBUTION OF MICROLENSING SURVEYS TO THE DISTANCE SCALE

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Abstract. In the early nineties several teams started large scale systematic surveys of the Magellanic Clouds and the Galactic Bulge to search for microlensing effects. As a by product, these groups have created enormous time-series databases of photometric measurements of stars with a temporal sampling duration and accuracy which are unprecedented. They provide the opportunity to test the accuracy of primary distance indicators, such as Cepheids, RR Lyrae stars, the detached eclipsing binaries, or the luminosity of the red clump. We will review the contribution of the microlensing surveys to the understanding of the physics of the primary distance indicators, recent differential studies and direct distance determinations to the Magellanic Clouds and the Galactic Bulge.

1. Introduction

The distance scale problem has been in the center of one of the most heated debates in Astronomy this century and, despite enormous efforts, up to this day large systematic effects remain between several different distance indicators. Following Aaronson & Mould (1986), we recall that “the ideal distance indicator:
1. should satisfy small quantifiable dispersion;
2. should be measurable in enough galaxies so that it can be calibrated locally, and its intrinsic dispersion and systematic variation can be tested;
3. should have a well defined physical basis;
4. should be luminous enough to be useful at large distance.” The microlensing surveys give us the opportunity to test the accuracy of primary distance indicators, such as Cepheids, RR Lyrae stars, the luminosity of the red clump, ... Thanks to their systematic observations of millions of stars, it is possible to build complete catalogues of variable stars or color magnitude diagrams (CMDs hereafter) in different galaxies of different metallicities and different star formation histories.

Heroic efforts from the ground (Pierce et al. 1994) or with the Hubble Space Telescope (see other chapters in this volume) give samples made of a few dozen of Cepheids at maximum in a given very distant galaxy with a small number of epochs. On the contrary, the microlensing surveys provides high accuracy light curves with extremely good phase coverage for periods of years for millions of stars (thousands of Cepheids and RR Lyrae stars) in different nearby galaxies. They provide strong constraints at different metallicities for the theory of stellar pulsation and stellar evolution. Therefore they help our understanding of the physical basis of these distance indicators. They offer a very good basis for differential studies and for checking the consistency between the different primary distance indicators.

2. Microlensing surveys

Following an original idea proposed with skepticism by Einstein in 1936 and revived in 1964 by Refsdal, Paczyński (1986) suggested to probe our Galactic Halo via microlensing effects on stars in the Magellanic Clouds. A compact object in the Galactic Halo passing close enough to the line of sight to a background star in the Magellanic Clouds induces an increase in the apparent brightness of the star. This phenomenon occurs owing to the alignment of the observer, the deflector, and the background star. If the total mass of our halo is in the form of compact objects, the probability of a star to be amplified by at least a factor 1.34 is $0.5 \times 10^{-6}$. Assuming a co-rotating halo, the time scale $\tau_0$ of an event is given by $\tau_0 = 70 \sqrt{M/M_\odot}$ days where $M$ is the mass of the deflector. Therefore in order to be sensitive to a wide range of masses for compact objects, one should monitor millions of stars and be sensitive to events with time scale ranging from hours to years. The choice of a line of sight towards the LMC and one towards the SMC would give information about the geometry of the halo (Sackett & Gould, 1993). Moreover it is also interesting to monitor stars towards the galactic center. It provides a proof-of-principle for the experiment because microlensing is expected from the known faint end of the stellar luminosity.
Moreover, the probability of seeing MACHOs is not much less than that expected towards the LMC. In the early nineties, the technology needed to perform such a search become available and three teams decided to enter the game: EROS, MACHO and OGLE.

EROS (Expérience de Recherche d’Objets Sombres – Aubourg et al. 1993) is a collaboration between French astronomers and particle physicists. They adopted two strategies: the first involves the photographic monitoring of a 25 square degree field in the LMC using ESO Schmidt plates. Exposures have been taken no more than nightly in two colors, \(B\) and \(R\). About 380 plates have been taken between 1990-1994. The second approach uses a 0.4m f/10 reflecting telescope and a mosaic of 16 buttable CCDs covering a field of \(1 \times 0.4\) degree centered in the bar of the LMC and in the main core of the SMC. Between 1991 and April 1994, about 15,000 images have been taken in two broad band filters, \(B_{E}\) and \(R_{E}\), and 250,000 light curves with as many as 48 points a night have been obtained.

The MACHO collaboration (Massive Compact Halo Objects – Alcock et al. 1993) has the dedicated use of a 1.27m on Mount Stromlo (Australia). They equipped it with a prime focus reimager-corrector with a dichroic beam splitter which provides a \(1^\circ\) field in two passbands simultaneously. In each beam they have one \(2 \times 2\) array of \(2048 \times 2048\) Loral CCDs covering 0.5 square degrees. They started the operation in 1992 with the LMC as prime target (monitoring 9 million stars), then the Bulge (monitoring eleven million stars) and the SMC. They adopted a daily sampling rate, or a few points a week, to be sensitive to MACHOs in the mass range \(\sim 10^{-3} - 10^{-1} M_{\odot}\). The observations will stop at the end of this millennium.

OGLE (Optical Gravitational Lensing Experiment – Udalski et al. 1992) had on average 75 nights/year a 1m telescope at their availability at Las Campanas (Chile) between 1992-1995. This telescope was equipped with a \(2048 \times 2048\) Ford/Loral CCD chip with a full frame of \(15 \times 15\) arcminutes. They used two filters, an I band filter which is closely related to Gunn \(i\) and a \(V_J\) filter, though the vast majority was done in I. Their primary objective was to search for microlensing events towards the Galactic Bulge. They monitored approximately two million stars in the Galactic Bulge and reported a total of 19 microlensing events in their first four seasons.

The first microlensing events towards the LMC and the Galactic Bulge were announced almost simultaneously in October 1993 by EROS, MACHO and OGLE. Now these event are discovered on a nearly daily basis toward the Bulge and a dozen have been observed toward the LMC and the SMC.

Another microlensing survey started soon after the three pioneers: DUO (Disk Unseen Objects – Alard & Guibert 1997). Two hundred Schmidt plates covering a field of 25 square degrees centered at the galactic coordinates \(b=-7^\circ\), \(l=3^\circ\) have been taken in 1994. Despite the use of photographic
plates, this survey has been very successful thanks to a powerful photometric package developed specifically for the experiment (Alard 1996). Part of the EROS schmidt plates have been reprocessed with this package and a catalogue of 10000 LMC RRLyrae will be released soon (Alard, Beaulieu, Lesquoy & Hill, in progress).

EROS and OGLE have been upgraded recently and entered the EROS-2 and the OGLE-2 phase. EROS-2 uses the dedicated Marly 1m telescope at ESO La Silla. The prime focus is equipped with a focal reducer and a dichroic beam splitter with a mosaic of eight CCD $2048 \times 2048$ in each channel. The total field is $0.7 \times 1.4^\circ$. The collection of data started in July 1996 with the SMC as prime target. EROS-2 observes the LMC, SMC, the Galactic Bulge (with sampling rate daily, or few points a week). It performs a search for red dwarves by proper-motion measurements and a type Ia supernova search.

The second phase of the OGLE project, OGLE-2, uses the new dedicated 1.3 m Warsaw Telescope at Las Campanas, which saw first light on February 1996, with regular observations starting almost one year later. As described in Udalski et al. (1997) the CCD camera used is a $2048 \times 2048$ pixels in drift scan mode. In contrast to the first four pilot years, the OGLE-2 team will be looking for microlensing not only in our own Galaxy but also towards LMC and SMC. The data flow is expected to increase 30 fold in comparison with OGLE-1.

At least three other microlensing surveys appeared recently, but have not provided yet any non-microlensing results to our knowledge. VATT-Columbia is searching microlensing in M31 by the image subraction technique (Tomaney 1997). AGAPE (Ansari et al. 1997) also observed M31, but with a different technique called pixel lensing (monitoring of the actual pixel flux). MOA (Abe et al., 1997) is a Japan/New-Zealand collaboration planning to search for microlensing towards the Magellanic Clouds and the Galactic Bulge. In 1995 appeared two microlensing follow-up networks, PLANET (Albrow et al. 1997) and GMAN (closely related to MACHO). They are doing accurate, multi-site observations on on going microlensing events to detect anomalies in the light curves that could be due to blending, parallax, binaries, or planets. For details about the results of microlensing surveys, see Paczyński (1996), Ferlet & Maillard (1997), and the web sites listed in the bibliographic section.

The real strength of microlensing experiments is to realize a systematic photometric survey of millions of stars over long period of time. However we should stress one of their general weaknesses: these experiments are specifically made to search for microlensing events. Hence EROS and MACHO adopted wide band filters in order to get more photons and therefore were able to monitor more stars improving the statistics for microlensing.
In the case of the EROS experiment for data taken between 1991-1995, the filters $B_E$, $R_E$ can be transformed to the standard system (V, I). 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 420-720 nm and 620-920 nm. They are so wide that a reliable transformation between this system and a standard UB-VRI will be very difficult, or even impossible, to determine. MACHO also have very wide band filter system for reasons similar to EROS and detailed calibrations have not been published yet. EROS-2 and MACHO generate homogeneous very large databases in their own photometric system, but comparison with other observations, models, temperature calibrations, are not trivial at all.

The strategy adopted by OGLE and OGLE-2 is much more attractive than the ones from MACHO and EROS-2 from a non-microlensing point of view: they observe with standard filters and provide accurate calibrations in BVI for their catalogues. Moreover OGLE have made a real effort in order to make their data accessible as soon as possible. One example is the early release of a catalogue of BVI measurements of two millions stars in the central part of the SMC as part of the OGLE-2 survey.

3. A better understanding of the physics of distance indicators

Thanks to the systematic searching aspect of the microlensing surveys, large sample of primary distance indicators have been built in galaxies of different metallicities. In the case of the pulsating variable stars, these large samples offer new tests to the theory of stellar pulsation/stellar evolution and opacity tables and therefore will help our understanding of these indicators.

Because the Cepheid period luminosity relation is the corner stone of distance determination since the beginning of the century, most effort has been devoted to this class of variable stars. We will also present the current status of the different studies of RRLyrae variable stars.

3.1. THE CEPHEID CASE

Cepheids are young, intermediate mass (typically $2−10M_\odot$), bright periodic variable stars. These stars have left the main sequence and are in a post core hydrogen-burning phase. Because of this evolutionary stage, they lie in an area of the HR diagram, the so-called instability strip, where their envelopes are instable to kappa mechanism. They develope radial pulsations. Their period of pulsation is correlated with their luminosity, and this period-luminosity relation (PL) has been used as the corner stone in deriving local distances, and extragalactic distances for decades.
A Cepheid envelope is an acoustic cavity in which an infinity of modes of pulsation exist. However very few of them contribute to the dynamics of the system; the unstable modes and the marginally stable modes coupled 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 and about the resonances between pulsational modes.

Two large Cepheid catalogues were built from EROS observations (550 Cepheids in the LMC and the SMC – Beaulieu & Sasselov 1997 and references therein), MACHO observations (1466 Cepheids in the LMC – Welch et al. 1997 and references therein) and from a pilot campaign of EROS-2 observations (∼900 LMC and SMC Cepheids – Bauer et al. 1998).

It was known for years that the Cepheids divide into two groups, the Classical Cepheids with rather high amplitude, asymmetric curve, and the so-called s-Cepheids, with low-amplitude symmetric light curves. Following the suggestion of Antonello et al. (1986), Beaulieu et al. (1995) showed that this morphological classification is mirrored by a dichotomy in the period-luminosity plane: the classical Cepheids are fundamental pulsators whereas s-Cepheids are first overtone pulsators. Just on the basis of the light curve shape, it is possible to distinguish between Cepheids pulsating in different modes.

3.1.1. Classical Cepheids, s-Cepheids, and Beat Cepheids

In our Galaxy, the LMC, and the SMC, we observed the Hertzsprung progression of the changing form of Cepheid light curves due to a 2:1 resonance between the fundamental and the second overtone (also known as the bump Cepheids). This resonance takes place at 10±0.5 days in our Galaxy. Using data obtained by the MACHO, EROS, and EROS-2, the resonance takes place between 10.5-12 days. The resonance in the SMC takes place in the range 10.5-13.5 days (the upper value being poorly constrained).

The s-Cepheids (first overtone pulsators) have been observed in the three galaxies. They present the same evolution of light curve with period, alleged to be the signature of a 2:1 resonance between the first and the fourth overtone. It takes place at 3.2 ± 0.2 days in our Galaxy, 2.7 ± 0.2 days in the LMC, and 2.2±0.2 days in the SMC. One can notice that unlike for fundamental pulsators, the resonance is taking place at shorter periods when going to lower metallicity.

So far 73 beat Cepheids have been found in the LMC by MACHO (Welch et al. 1997 and references therein), eleven in the SMC by EROS (Beaulieu et al. 1997) and fourteen are known in our Galaxy (Pardo & Poretti 1997 and references therein). They are pulsating either in the fundamental and first overtone mode (F/1OT hereafter) or the first and second overtone mode
(1OT/2OT hereafter). The SMC 1OT/2OTs are very similar to the LMC ones while the SMC F/1OTs have period ratios systematically higher than the LMC ones by $\sim 0.01$ which are systematically higher than the Galactic ones by $\sim 0.01$.

3.1.2. Searching for consistency between the theory of pulsation, evolution and opacities

With two kinds of beat Cepheids, plus the two resonance constraints on the classical Cepheids and the s-Cepheids observed at different metallicities, we are probing different depths in the Cepheid envelopes, and drawing new strong constraints (similar to helioseismology) for the theory of stellar pulsation, stellar evolution and the opacity tables at low metallicities.

When going to lower metallicity, the $\sim 10$ days resonance for fundamental Cepheids occurs at longer periods, whereas the resonance at $\sim 3$ days for overtones occurs at shorter and shorter period. The period ratios of F/1OT beat Cepheids increases when decreasing the metallicity, whereas they are the same for 1OT/2OT for LMC and SMC.

From a theoretical point of view, one has to keep in mind that when going to lower metallicities, the evolutionary models will increase the luminosity at a fixed mass. The increase of mass will lead to a diminution of the calculated period ratios. However when going to lower metallicity, the opacity bump that drives the pulsation will be smaller and therefore will increase the period ratios for a fixed mass and luminosity. However since the different modes of pulsations are probing different depth in the Cepheid envelope, the net effect will be different from mode to mode. The final result, the observed position of a resonance center will be a combination of these antagonistic effects (plus a possible non-linear shift, particularly in the case of resonance coupled modes).

The determination of the Cepheids masses has been a long standing problem. Serious discrepancies existed between masses from evolutionary theory and pulsation theory. The well-known mass problem of the Cepheids (for a review, see Cox 1980) led Simon to suggest a revision of the opacities (Simon 1982; Andreasen 1988). The use of improved opacities (OPAL – Iglesias et al. 1992; OP – Seaton et al. 1994) has substantially decreased the mass discrepancy but not totally removed it. Perhaps more importantly, the bump Cepheids have revealed a strong sensitivity to the recent opacities and the mixture. (Moskalik et al. 1992, Simon & Kambur 1994). The strong sensitivity to opacities makes it a useful tool to test the opacities at different metallicities using extragalactic Cepheids.

The presence of two pulsating modes in the envelope of a Cepheid gives an anchor for pulsation theory: it is possible to obtain the luminosity and the mass independently of any evolutionary model, given the temperature
and the chemical composition. Buchler et al. (1996) showed that the implication of the 2:1 resonance between the fundamental and the second overtone around ten days for the Bump Cepheids, the alleged resonance around three days for the s-Cepheids are difficult to reconcile with the envelope models at low metallicity (Z=0.01 and Z=0.004) with the OPAL93 opacities. When going to lower metallicities the derived masses are too small. The discrepancy increases when decreasing the metallicity. Whereas a single mass-luminosity relation (ML) is able to reproduce the extent of the instability strip, there remains some discrepancy for the Bump Cepheids of the Galaxy, i.e. the mass still differs by \(~10\%\) as compared to evolutionary models using the same set of OPAL opacity tables. This discrepancy (whatever its origin) can be quantified as an increase of the overshoot parameter. However an increase of the overshoot parameter in the evolutionary models (suggested by Chiosi et al. 1993 as a solution of the Cepheid mass problem) will be in strong disagreement with other observational constraints. In contrast for the LMC and the SMC, not only the zero point of the ML leads to disagreement with evolutionary models mass discrepancy of about \(1-2M_\odot\) but single ML relation cannot render count of the width of the instability strip. The OPAL95 version includes several improvements among which the incorporation of seven additional chemical elements of the iron group have been resulted in a further increase of the opacities (20\%) compared to the OPAL93 version in the region of the Z-bump which is relevant for the Cepheids. A similar survey done with this new set of opacities shows that the situation improved, but the discrepancy is not removed. Meanwhile the results coming from survey of radiative hydromodels at low metallicity suggest that a strong dissipative mechanism is missing in the envelopes.

Some studies have been focusing on the beat cepheids at different metallicities (Morgan & Welch 1997; Christensen-Dalsgaard & Petersen 1995; Antonello et al. 1997; Baraffe et al. 1998). In these studies several mass-luminosities relation from evolutionary calculations or ad hoc choices are adopted, linear stability analysis of the envelope with pure radiative, of convection with mixing length theory are performed. Then they generally concludes that they Beat-Cepheids period-period ratio planes are reasonably well reproduced for the galaxy, LMC, SMC metallicities. In fact, using their iterative code, Buchler et al. (1996) showed that at best beat Cepheids give weak constraints on mass luminosity relation. They provide a useful set of tests for stellar pulsation theory, but they cannot be used as a strong constraint on ML relations, unlike the ten-day resonance.

Several attempts to model the resonance at \(~3\) days for overtone pulsators using radiative hydro models (Buchler, private communication; Antonello & Aikawa 1995) have so far failed, showing unphysical “spikes” in the light curves.
The second overtone mode has been observed in Beat Cepheids. Therefore it is natural to ask the question whether single mode second overtone pulsators exist. No answer has been given yet from an observational point of view, but Antonello & Kanbur (1997) made a survey of hydro models to study these hypothetical stars and predict resonance positions and characteristics of the light curves (but again with unphysical features in the light curves).

Over these last years, it has become increasingly clear that there are a number of severe problems with radiative models (cf. Buchler 1998). A strong dissipative mechanism is missing in the envelope calculations. The inclusion of a recipe of turbulent convection in stellar envelopes (Gehmeyr & Winkel 1992; Bono & Stellingwerf 1994; Bono & Marconi 1998; Yecko et al. 1998) is promising. The implementation of a relaxation method to obtain non-linear periodic pulsation and stability analysis of the limit cycles is much more powerful than very time consuming and sometimes inconclusive hydrodynamic integrations. The first hydro models of Beat Cepheids ever computed (Kollath et al. 1998) reproduce period ratio, modal amplitude and their ratios thanks to full hydrodynamic integration and the relaxation method. After 30 years of failure with radiative models, it turns out that the Beat Cepheid phenomenon is natural and very robust once turbulent convection is implemented. Moreover preliminary results show that the Cepheid mass problem is removed (Beaulieu et al., in preparation) for the SMC and LMC metallicities. Thanks to the new constraints raised by the microlensing surveys at different metallicities, significant progress has been made on the theory of stellar pulsation. We feel that turbulent convection puts the nail in the coffin of Cepheid radiative models...

3.1.3. A theoretical calibration of the Cepheid PL

Several efforts are on going in a try to produce a theoretical calibration of the Cepheid PL relation at different metallicities. It is definitively a difficult challenge, involving up to date opacity tables, proper set of evolutionary models for the different metallicities, stellar envelope calculations taking into account the different constraints given by the position of the resonance centers and the beat Cepheids at different metallicities. Once all these constraints on the modelisation of the envelope have been met successfully, then stellar atmosphere calculations have to be performed and “put on top” of the stellar pulsation calculations. Currently (and for the next few years) these would have to be static atmosphere calculations. The complete modelisation of a dynamic envelope and atmosphere of a Cepheid is currently still a dream.

The classical study of Chiosi et al. (1993) has been the reference for distance scale studies over the last years. They computed a large grid of
Cepheid models varying mass, effective temperature, initial chemical composition (Galaxy, LMC, SMC, ...) and mass-luminosity relations (with mild or large core overshoot). The linear non-adiabatic stability analysis of the Cepheid envelopes with a treatment of convection by the mixing length theory was performed, using the (now obsolete) Los Alamos opacities. They derived relations between luminosity, effective temperature and UBVRI magnitudes by using theoretical atmosphere models. Among the results from their survey, they show that the Cepheid PL show a small dependence of metallicity if one uses the V and I bands, whereas the dependence is important if one uses B and V. This work has been quoted extensively and used as a strong case to neglect metallicity effects on the Cepheid PL when using V and I photometry. However, it is worth mentioning that nonlinear, nonlocal and time-dependent convective pulsating models are needed to predict accurate determinations of both blue and red edges of the Cepheid instability strip and that we should wait for these models to have a good theoretical understanding of metallicity effects on the PL relations.

Baraffe et al. (1998) present a systematic survey of evolutionary models and pulsational models in an effort to provide a theoretical calibration of the Cepheid PL relation at different metallicities. They performed an extensive survey of evolutionary calculations for masses in the range $3 - 12M_\odot$ for $Z=0.02, 0.01, 0.008, 0.004$. The evolutionary calculations are coupled with a Linear-Non-Adiabatic stability analysis with standard mixing length theory. They reproduce the period-period ratio diagrams for beat Cepheids with good agreement, on the other hand they do not comments on the position of the resonance centers obtained by their modeling.

Bono & Marconi (1998) adopted the same ML relation for different metallicities, because they consider that the uncertainty connected with the Helium fraction and the heavy elements in the ML relation, are of the same order as the decrease/increase in the luminosity caused by the metal abundance. Then they compute a survey of hydro models including non linear non local time dependent turbulent convection, derive observable quantities from static stellar atmosphere models, and provide a theoretical calibration of the Cepheid PL at different metallicities. Even if several uncertainties remain in the evolutionary calculations, the difference of metallicity will imply systematic shifts in the ML relations which will have a direct impact on any attempt to derive a theoretical PL relation.

3.2. THE RRLYRAE CASE

Low-mass stars ($< 0.8M_\odot$) descending the Red Giant Branch (RGB) and having a rather thin envelope will settle on the Horizontal Branch (HB) after the onset of He core burning. These stars are liable to envelope in-
stabilities. These instabilities are driven by He ionization zone and result in radial pulsations. The evolutionary loci in the H-R diagram where these stars are found is termed the instability strip. The instable region in the H-R diagram depends on the stars exact chemical composition and mass.

These RRLyrae variables which are often found within Globular Clusters (hence the synonym: cluster variables) are of the low metallicity population II and have periods ranging from 0.2 to 1.2 days with amplitudes below two magnitudes. Their behavior form an excellent opportunity for developing and testing current ideas on pulsation theories, stellar HB evolution and HB morphology.

As with the Cepheid case one can distinguish different kinds of subtypes, depending on the exact mode in which the stars are pulsating. Phenomenologically one can distinguish these types on the basis of their lightcurves and periods. Using Fourier decomposition, the observed population of RRLyrae stars are differentiated into four basic types. Stars of type RRab are the fundamental mode pulsators, type RRc constitute the first overtone pulsators, and type RRd are double mode pulsators. Fourier decomposition is a powerful tool in addressing the classification method, though good phase coverage and marginal errors of a lightcurve are required for optimal efficiency of this method.

The internal constitution of the RRLyrae variable stars and the way the instabilities cause the radial pulsations are reasonably well understood though understanding of a view long standing problems still remain. One of these phenomena is the well known elusive variation of the light curve of RRab’s in amplitude and shape, the Blazhko effect. Different models have been proposed, like Cousens’ (1983) of the oblique magnetic rotator and Moskalik’s (1985) of mode resonances, but none has been appreciated yet. But generally speaking the RRLyrae stars form a very important distance indicator for Globular Clusters, LMC and galaxies within the Local Group, due to their regular pulsation mode and their absolute brightness of approximately +0.8 magnitudes. A good calibration for the absolute visual magnitudes with the pulsation period is of cardinal importance for global distance indications. A synthetic correlation (pulsation equation) of the pulsation period of the star to its stellar parameters, $P_0=P_0(L,T_{\text{eff}},M)$, was reported in the classic paper by Van Albada & Baker (1971), marking the start of the controversy between the luminosity of HB stars derived from evolution theory and from pulsation theory. In view of this an important discovery was made by Sandage (1982), which is termed the Sandage-Period-Shift: the increase of the RRLyrae pulsation period with a decrease of the metallicity.

In the following years extensive studies have been devoted to the calibration of the RRLyrae absolute luminosity and the parameters it depends
on, observationally as well as computationally. One of the main objectives is to find the dependency of $M_v(\text{RR})$ on [Fe/H] (Rood 1990; Sandage 1993; Carney, Storm & Jones 1992) and where it is shown by Caputo (1997) that this relation is dependent on the exact morphology of the HB which is quantified by Lee (1989) in the parameter $(B - R)/(B + V + R)$, where B, R, and V are the number of red, blue and variable HB stars. She uses synthetic HB computations to predict the edges of the instability strip and computes the masses from globular clusters with known [Fe/H] and HB morphology. In this way an estimate for their distance modulus is made.

An observational technique for an empirical absolute magnitude calibration is presented by Kovács and Jurcsik (1997). They attempt to derive a linear equation for the distance moduli of the RRab stars on the basis of correlations between Fourier parameters and $<M_v>$, through the basic fact that the lightcurve is in some way related to the stellar parameters and thus should be reflection of them.

Series of elaborate theoretical investigations have been devoted to develop theoretical models on the behavior of these kinds of stars by Bono et al. (1997). With state-of-the-art hydrodynamical codes they present an atlas of full amplitude theoretical lightcurves accompanied by predictions for the limits in the H-R diagram of the instability strip and a updated linear pulsation equation. A study on the theoretical calibration for RR Lyrae with higher metallicity has been conducted by Bono et al. (1997) as evidence began to stack for high [Fe/H] popII pulsators (up to solar metallicity). Their results show an decrease in the amplitude of the first overtone mode with increasing [Fe/H] and an opposite correlation for the fundamental mode pulsation.

However the apparent success of hydrodynamical models simulating RRab stars has been challenged by Kovács & Kanbur (1998). They show that a overwhelming majority of the models tested does not follow the empirical relations derived from observations (e.g. Kovács & Jurcsik 1997) regarding the shape of the light curves and the physical parameters. This article “RR Lyrae models : mission (im)possible”, shows the actual limitation of the present theoretical scenarios.

The dawn of large observational photometric databases through the micro-lensing surveys have shed more light on longstanding problems within the variable star theories and have helped in constraining evolutionary and pulsation properties. They brought new developments and discoveries. One of these new developments concerns the second overtone pulsating RR Lyrae or RRe type. A few stars are suggested to be candidate RRe (Clement et al. 1979; Walker & Nemec 1996).

The MACHO collaboration reports a total number of $\pm 8000$ field RR Lyrae in the bar of the LMC (Alcock et al. 1996). They argue for a signif-
icant distribution of RRc type stars in the period distribution of their LMC fields, with a mean period of 0.281 days. They claim that the lightcurve of this population component shows an asymmetric and low-amplitude profile, distinguishable from the other type lightcurves. The MACHO inferences are disputed by Kovács (1998). In his paper he makes a case for the RRc’s being first overtone pulsators (RRc’s) based on the light curve (no outstanding different features) and computational evidence from pulsation, evolution and atmosphere calculations, but he acknowledges the reality of the MACHO distribution, suggesting that the explanation of the shape lies in the metallicity dependent HB evolution.

4. Distance determination from microlensing surveys

4.1. BAADE-WESSELINK DISTANCE TO THE LMC

Several groups are trying to get distance determination of the Magellanic Clouds based on different variant of the Baade-Wesselink method. The catalogues of Cepheids created by EROS, EROS-2, MACHO and OGLE-2 offer or will offer the light curves of a very large number a Cepheids that can be used for Baade Wesselink distance determination. We will just mention two recent contributions to the field.

Gieren et al. (1998) used the near-infrared Barnes-Evans surface brightness technique with a zero point of the surface brightness color relation determined from a large set of interferometrically determined angular diameters of cool giants and supergiants (Fouqué & Gieren 1997). They are using independently two magnitude-color combinations (K, J-K) or (V, V-K) and existing radial velocity curves. Therefore they derive two independent solutions that are consistent at a remarkable level and got a LMC distance of $18.46 \pm 0.02$. To include uncertainties for metallicity effects or other systematics, they give a “conservative” LMC distance of $\mu_{\text{LMC}} = 18.46 \pm 0.06$.

Krockenberger et al. (1997) developed a new approach of the Baade-Wesselink method: using HR spectrum and hydro models of Cepheid atmospheres they have good understanding of the dynamics of the asymmetry of the spectral lines, and therefore can provide very accurate radial velocity curves. They want to reduce the systematic errors in the measurement of the surface brightness and the temperature by the use of HR spectrum (instead of color indexes). They then adopt a rigorous statistical approach to determine properly the radius and the distance of the target stars. First overtone pulsators from the EROS microlensing survey have been observed, and preliminary results presented (Krockenberger et al. 1997). The LMC distance could be determine with an accuracy of 3%. In the near future, this method will be used to determine the distance of M31 and M33 with an accuracy of 6% using high quality photometry obtained by DIRECT (a
systematic survey searching for Cepheids in M31 and M33 – Kaluzny et al. 1998; Stanek et al. 1998a) and Keck spectroscopy.

4.2. MULTI-MODE RR LyRAE

Jorgensen & Petersen (1967) were the first to recognize the possibilities a double mode pulsating star would open. As they write in their paper, these stars create the opportunity to make a mass estimation founded on the ratio of the periods of first overtone to fundamental mode (by means of the Petersen diagram (PD), which couples $P_1/P_0$ to $P_0$ on the abscissae). Logically this method yields important consequences for evolutionary and pulsation scenarios.

Bono et al. (1996) showed that the PD is a valid technique for estimating the RRd masses. They claim that the best approach for the removal of the mass discrepancy existing in the used physical route (evolution, pulsation) is by using the non-linear, non-local, time-dependent convective models for the RRd variables. (However they do not compute real double-mode RR Lyrae stars. Given the initial perturbation, they converge either to a fundamental or first overtone mode).

Observationally with the report of 73 double mode RR Lyrae stars by Alcock et al. (1997), their total number was almost doubled. In the MACHO LMC fields, RRd’s were discovered with fundamental periods between 0.46-0.55 days and $0.742 < P_1/P_0 < 0.748$, founded on rough selection criteria. In the study of these objects they use PD estimated masses, the theoretical pulsation equation of Bono et al. (1997) and the assumption of a similarity between the temperature of RR Lyrae stars at the blue edge (Sandage 1993a&b) of the instability strip and the temperature of the RRd’s, to arrive at a PL relation. Finally a distance measurement of the LMC is straightforward, setting the multimode pulsating RRd based $\mu_{LMC}$ to $18.48 \pm 0.19$. We recall that the LMC distance based on single mode RR Lyrae (cf. Layden, this volume and references therein) is $18.28 \pm 0.13$.

4.3. DISCOVERY OF AN EXTENSION OF THE SAGITTARIUS DWARF GALAXY

Alard (1996) analyzed the Schmidt plates data obtained for the DUO microlensing survey. They cover a field of 25 square degrees centered at the galactic coordinates $b=-7^\circ$, $l=3^\circ$. He discovered 1466 RR Lyrae displaying a bimodal distribution of magnitude with two clumps separated by 2.3 mag. He assumes that all RRab have the same color at minimum light and correct for extinction. It even reinforce the bimodality of the distribution. Moreover stars in the two peaks of the distribution follow different period histograms, indicating a different metallicity. Most of the RRab belong to the Bulge and
313 stars are concentrated at 24 kpc, which is consistent with an extension of the recently discovered Sagittarius dwarf galaxy (Ibata et al. 1994). Mateo et al. (1995) measured the distance of this galaxy with CMDs to be $25 \pm 2.8$ kpc. Mateo et al. (1996) and Alcock et al. (1997c) found that the Sagittarius dwarf galaxy has an elongated main body extending far from his core, for more than 10 kpc.

4.4. THE RED-CLUMP METHOD

The red-clump stars are the counterpart of the older horizontal branch in globular clusters and represent a post Helium flash stage of stellar evolution (Chiosi et al. 1992). Paczynski & Stanek (1998, PZ98) proposed to use the luminosity of the red clump as a distance indicator. They compared the absolute magnitude in the I band of about 600 nearby red-clump stars observed by Hipparcos with accurate trigonometric parallaxes in the solar neighborhood and apparent magnitude of red-clump stars observed by OGLE in the Baade window to have a single step determination of the galactocentric distance. Empirically they found that the average I band magnitude of clump stars does not depend on their intrinsic color in the range $0.8 < (V - I)_0 < 1.4$ in the Baade Window. Then they assume no reddening for their calibrator (clump stars in the solar neighborhood) and use the reddening maps of Stanek et al. (1996) and Alcock et al. (1998a) for the Baade window. We stress that one of their key assumption is that the two populations of the red clump (calibrator and target) follow the same luminosity function. Then they directly compare the two populations. They get a distance determination to the galactic center of $R = 7.97 \pm 0.08$ kpc.

The OGLE-2 team observed four drift scan strips in the SMC, each of them covering $14.2' \times 57'$ (100 000-150 000 stars per field) and 4 drift scan strips in the LMC (same angular size, about 200 000 stars per strip) in BVI. They built the color magnitude diagrams for these fields. They adopt a mean reddening of $E(B-V)=0.09$ for their SMC fields and used the reddening maps from Harris et al. (1997) for their LMC observations. They use the red-clump method following the precepts of PS97 and derive a very short distance to the LMC and to the SMC, about 0.4 mag shorter than the generally accepted distances. $\mu_{LMC} = 18.08 \pm 0.03 \pm 0.12$ and $\mu_{SMC} = 18.56 \pm 0.03 \pm 0.06$.

Stanek et al. (1998b), using an independent data set of LMC observations over a wide field of $2 \times 1.5$, applied exactly the same method and reached a similar conclusion, $\mu_{LMC} = 18.065 \pm 0.031 \pm 0.09$.

Beaulieu & Sackett (1998) showed that the red clump observed by Hipparcos is well reproduced by the isochrones from Bertelli et al. (1994) with the distance derived by PZ98, but adopted a LMC distance of 18.3 as a
best match of the LMC red clump.

Cole (1998) and Girardi et al. (1998) proposed a detailed study of possible systematic errors in the distance determination using the red-clump method to show that, with the current evolutionary calculations, it is not reasonable to assume that the luminosity function of the red clump does not depend on age, chemical composition, mass loss, star formation history. Cole proposes some corrective terms to the determination of Udalski et al. (1998) and derives a LMC distance of 18.36 ± 0.18.

4.5. DETACHED ECLIPSING BINARIES

Hilditch (1995) and Paczyński (1996) showed that the observation of detached eclipsing binaries with deep narrow primary and secondary eclipses, without anomalies in the curve, combined with follow-up spectroscopy is a very accurate primary distance indicator. However such systems are rare and difficult to detect. Grison et al. (1995) present a catalogue of 80 eclipsing binaries discovered by EROS in the bar of the LMC, Alcock et al. (1997a) present the MACHO catalogue of 611 eclipsing binaries in the LMC. These two catalogues provide good candidates that could be used for an accurate distance determination of the LMC. Pritchar et al. (1998) based on the observation of two systems, derive a distance to the LMC of 18.44 ± 0.07. Kaluzny et al. (1995) discovered eclipsing binaries at the main sequence turn-off point of Omega Centauri. The accurate observations of these stars will not only provide a distance determination to this cluster, but will also give us strong constraints on stellar evolution calculations. We also recall that detached eclipsing binaries are being searched in M31 and M33 in the framework of the DIRECT project (Kaluzny et al. 1998; Stanek et al. 1998a).

5. Differential studies

Homogeneous catalogues of large number variable stars and CMDs from microlensing surveys in different galaxies of different metallicities start to become available. They offer the opportunity to test the consistency between different distance indicators or to realize sophisticated differential studies.

5.1. EROS : METALLICITY EFFECT ON THE CEPHEID PL RELATION

The same method (Madore & Freedman 1991), based on multicolor photometry to determine reddening corrected Cepheid distances, has been adopted by HST distance scale programs (Freedman et al. 1994; Tanvir et al. 1995; Sandage et al. 1994). It is assumed that the Cepheid PL relation is universal
and that the Cepheids from the calibrating set and from the target galaxy have the same colors. The wavelength slopes of a calibrating set of LMC Cepheids are calculated. The PL relation of the Cepheids from the target galaxy is slid against it to derive apparent distance modulus in each band. A true distance modulus of $\mu_{\text{LMC}} = 18.5\text{mag}$, a mean reddening of $E(B-V) = 0.10$ and a Galactic extinction law with $R_V = 3.3$ are adopted for the LMC. Then using the multicolor apparent distance modulus and a Galactic extinction law, the total mean reddening and the true distance modulus of the target galaxy are determined.

However, presently available theoretical predictions, suggest that the slopes of the PL relation are independent of metallicity, only the zero-point is affected, and the metallicity effect depend on band pass. If one interprets the color shift due to metallicity as reddening in deriving the true distance modulus of a target galaxy with the method described above, then one makes a systematic error of $\delta \mu = -\delta M_V + R_V \delta(B-V)_0$, $(\delta(B-V)_0$ is the color change due to metallicity).

Observational studies have been made since the 70s. For example, an intrinsic color shift between LMC and SMC Cepheids has been pointed out clearly (Martin et al. 1979). An empirical search for a metallicity effect (Freedman & Madore 1990; Gould 1994) in three fields of M31 with 36 Cepheids and 152 BVRI measurements have led to ambiguous results: Freedman & Madore claimed that there is no significant effect. Gould reanalyzed their data with a better statistical treatment taking into account the high degree of correlation between the measurements and found an effect. However due to the number of observations, he was not able to solve for a wavelength dependence metallicity effect, and various systematics of the data set prevented him from deriving the size of this effect.

Beaulieu et al. (1997) and Sasselov et al. (1997) used the EROS Cepheids data from LMC and SMC to perform an empirical test for metallicity effect. They have high-quality, excellent phase covered light curves for classical Cepheids and s-Cepheids. Since they pulsate in different modes, they follow different PL relations. In the LMC they keep 51 fundamental pulsators and 27 first overtone pulsators, and 264 fundamental pulsators and 141 first overtone pulsators in the SMC. Thus they have two unbiased samples of Cepheids that fill densely the period luminosity color (PLC) space, with known difference in metallicity $\delta[Fe/H]_{\text{LMC-SMC}} = 0.35$.

Their method has been applied independently to classical Cepheids and s-Cepheids. First they compute wavelength dependent slopes for LMC and SMC Cepheids, these are the same within the error bars. They search for a metallicity effect that depends upon band pass. They model the data in the PLC plane taking into account the high degree of correlation between the measurements. The assumption of their model are constant PL
slope with metallicity, and no depth dispersion with the LMC sample. They adopted an LMC true distance modulus of 18.5 mag, a mean reddening of $E(B-V) = 0.10$ and a Galactic extinction law with $R_V = 3.3$. The model then has twelve parameters which are: a linear fit of the PL relation, a linear fit of the instability strip, the distance difference, the relative reddening difference and a metallicity dependence on the zero point of the PL relation.

They applied the technique to the Classical and the s-Cepheids independently and obtained exactly the same results. Metal poor Cepheids are intrinsically bluer, and this intrinsic color change due to metallicity is considered to be reddening when using the Madore & Freedman method to derive distances. They determined a corrective term due to the metallicity dependence to the Madore & Freedman distance determination method.

$$\delta \mu = (0.44^{+0.1}_{-0.2}) \log(Z/Z_{LMC})$$

Then they discuss its influence of the Hubble constant determination.

Kochanek (1997) applied a generalization of this technique to do a simultaneous fit to 17 galaxies. He derives also a significant metallicity correction to the Madore & Freedman method $\delta \mu = (0.4^{+0.2}_{-0.2}) \delta(O/H)$. Gieren et al. (1998), from observations of galactic Cepheids, suggest a metallicity correction of $\delta \mu \approx 0.2 \delta(O/H)$. Using HST observations of two fields of M101, the HST Key project on distance scale concluded that metallicity effects are the dominant source of error in their error budget, and derive a metallicity correction of $\delta \mu = (0.24^{+0.16}_{-0.06}) \delta(O/H)$. To nail down this problem, Cepheids in about half of the Key project galaxies will also have NICMOS observations.

5.2. OGLE-2: RRLYRAE AND THE RED-CLUMP METHOD

We would like to summarize a very recent differential study done by the OGLE team. Udalski (1998) uses OGLE and OGLE-2 observations of RRLyrae and red-clump stars in the Baade Window, the LMC and the SMC. He uses the RRLyrae calibrations from Gould & Popowski (1998) based on statistical parallaxes. He derives a weak metallicity dependence of the luminosity of the red clump (smaller than the theoretical predictions of Cole (1998) and Girardi et al. (1998), and found a good agreement between RRLyrae and red-clump distances which has independent calibrations. He derives the following distances from the RRLyrae: $\mu_{GAL} = 14.53 \pm 0.15$, $\mu_{LMC} = 18.09 \pm 0.16$ and $\mu_{SMC} = 18.66 \pm 0.16$ and from the red-clump stars: $\mu_{GAL} = 14.53 \pm 0.06$, $\mu_{LMC} = 18.13 \pm 0.07$ and $\mu_{SMC} = 18.63 \pm 0.07$. Udalski notes as a conclusion “it is a bit distressing that at the end of the 20th century one of the most important topics in the modern astrophysics, determination of the distance of the LMC – the
milestone for the extragalactic distance scale – is a subject of controversy as much as 15%”.

6. Conclusion

Already one conference has been entirely devoted to the by-products of microlensing surveys in July 1996 at the Institut d’Astrophysique de Paris (“The Astrophysical Return of Microlensing Surveys”, Eds. R. Ferlet & JP Maillard). Another conference (“The Impact of Large-Scale Surveys on Pulsating Stars Research”) will be held in Budapest in August 1999 and the microlensing surveys will have a preponderant part there.

The first contribution of the microlensing surveys to the distance scale problem is by generating complete samples of variable stars at different metallicities and color magnitude diagrams made of millions of stars. They help our understanding of the physics of the different distance indicators by giving strong constraints on the theory of stellar pulsation, stellar evolution and the opacity calculations. Maybe more important is the possibility to realize differential studies between different galaxies and different distance indicators. The goal is of course to check the accuracy of the different distance indicators used to obtain consistency between them, and finally to nail down the metallicity dependence and other possible systematic effects that poisoned the distance scale debate for decades.

Some very significant progress have been made on the Cepheid front. New strong constraints on the theory of stellar pulsation have been given, and we buried the purely radiative codes. Consistent calculations of evolutionary models, and up to date hydro codes including turbulent convection with the relaxation method are very promising. However complete dynamical atmosphere models to evaluate the proper bolometric corrections, colors and radial velocities for a better comparison with the observation are still missing. The differential studies of Cepheids between the LMC and the SMC based on EROS data showed the importance of metallicity effects on the Cepheid distance scale contrary to what was generally accepted. With two new methods, based on Cepheids observations, it is possible to determine the distance up to M31 and M33 with good precision. Large catalogues of Cepheids are already available, or will be released very soon.

Progress have been made too in the understanding of RRLyrae variables. The RRLyrae have shown to be a very powerful tracer of the population II in studying the structure of the Bulge, probing the extension of the Sagittarius dwarf galaxy or the structure of the LMC/SMC. Large number of double mode RRLyrae have been already discovered in the LMC, and provide a powerful test of stellar pulsation theory. An attempt of distance determination of the LMC based on calibrations of double mode RRLyrae
by models give a long distance to the LMC. On the other hand, single-mode RRLyrae still give a short distance to the LMC.

A new method based on the red-clump stars has been introduced. It gives results with a very small statistical error, whereas questions arise about the universality of the luminosity function and the influence of metallicity and of star formation history. Thanks to the very large number of clump stars available, it is very promising, but systematics must be carefully studied.

Large catalogues of variable stars of all kind are being built in a systematic way. Among them, detached eclipsing binaries will provide a powerful distance determination to the local group galaxies in a nearby future.

Under the cloak of the quest for dark matter, gold mines for stellar studies at different metallicities have been found. Mining is just really starting.

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