Chilean Astronomy is enjoying a rapid development due to increased funding and access to large telescopes.

Several current projects at different institutes in Chile will be presented in forthcoming issues of The Messenger. The following article is the first in the series.

A panorama of Chilean Astronomy will be presented in the next issue by Professor Leonardo Bronfman, President of the recently founded Sociedad Chilena de Astronomía.

Research in Concepción on Globular Cluster Systems and Galaxy Formation, and the Extragalactic Distance Scale

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1. Introduction

The Astronomy Group at the Universidad de Concepción is one of the youngest astronomical research groups in Chile. It was formed only six years ago and has grown steadily since. Currently, members of the Astronomy Group include four staff and four postdoctoral fellows. About a year ago, the Physics Department created a PhD programme, with astrophysics being one of the strongest groups in this programme. We are currently educating our first PhD students. Next year our Department will initiate an undergraduate degree programme in astrophysics. We expect that our staff and science activities, as well as the number of undergraduate and PhD students in astrophysics at the Universidad de Concepción, will be boosted in coming years by the recent creation of a FONDAP Institute which is shared by the three major Chilean Astronomy Groups, at the Universidad de Chile, Universidad Católica (both in Santiago), and at Concepción.

Two of our major current research areas deal with the distance scale and with globular clusters. About a year ago, CONICYT (the national science funding agency) approved financing of a 5-year research project for our group which seeks to increase the scientific interaction and scope, and strengthen the links between these areas. It is the purpose of this article to give the reader an impression of what we have been doing so far, and what our scientific goals are for the near future.

2. Research toward Improvements in the Distance Scale

Cepheid variables are generally considered as the best-understood and best-calibrated primary standard candles, and as such they have been widely used to determine distances to galaxies in reach of the Cepheid method (out to about 20 Mpc, at HST resolution). There are, however, still a number of important systematic uncertainties affecting both Cepheid variables and other secondary methods of distance measurement which have so far prevented a truly accurate calibration of the extragalactic distance scale. The astrophysical consequences of such a limitation include a larger uncertainty on the Hubble constant than we would hope for, after almost a century of hard work on this exciting and fundamental problem. The currently weakest link in the whole process of setting up the distance scale is our limited capability to measure truly accurate distances to nearby galaxies which provide the zero point calibration for the extragalactic distance scale. Our difficulties in determining absolute distances to nearby galaxies are best reflected by the current dispersion of the distance values derived for the LMC, the nearest (excluding Sgr) and best-observed galaxy. According to Gibson (2000), current values for the LMC distance modulus obtained with Cepheids, and a variety of other techniques, range between 18.2 and 18.8, corresponding to an embarrassing 30 per cent difference in distance between the extreme values. It is therefore mandatory to investigate, in much more detail, the true capabilities and systematics of the various techniques used to measure the distances to nearby galaxies. Only when these are fully understood, the techniques properly calibrated, with their dependence on environmental properties of the host galaxies (metallicity, age of stellar populations) taken into account, and agreement on the distances of a number of galaxies with a range of environmental properties has been achieved from the various methods, can we trust that the calibration of the local distance scale has finally been achieved with the required accuracy of a few per cent. In this process, we will also learn to distinguish the most accurate standard candles (those with the smallest intrinsic dispersions for distance measurement) from those less useful for distance de-

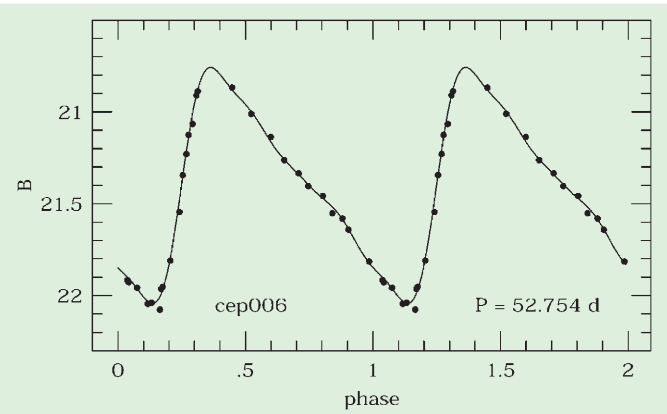

Figure 1: B light-curve of a typical Cepheid in NGC 300. The data were obtained with the ESO-MPA 2.2-m telescope and Wide Field Imager.

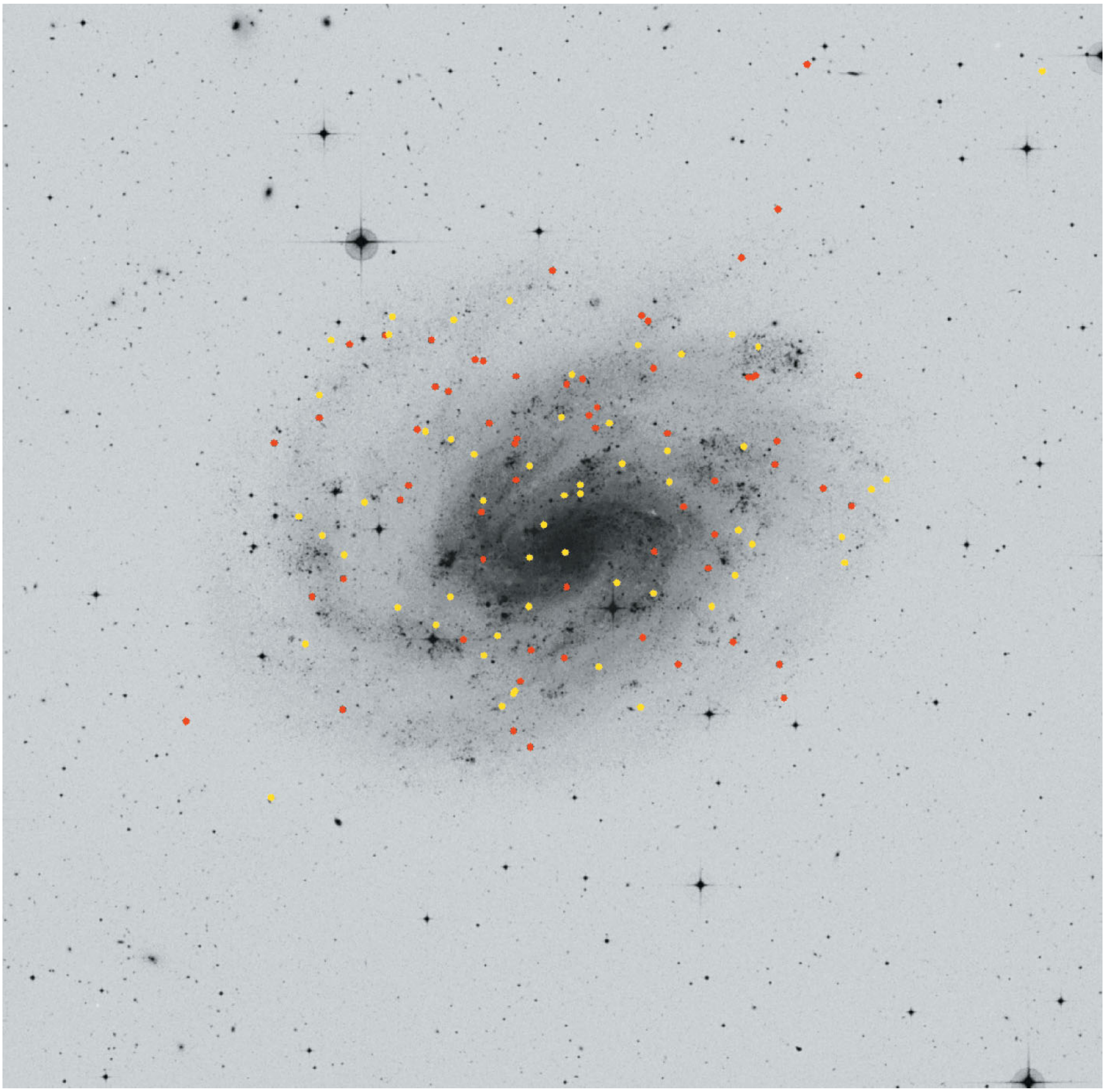

Figure 2: The Sculptor Group galaxy NGC 300, with Cepheids discovered by Pietrzynski et al. (2002) overplotted. Red and yellow points correspond to positions of Cepheids with periods smaller and larger than 15 days, respectively. North is up and east is to the left. The field of view is about 30 × 30 arcmin.

termination. As an added benefit, we will significantly improve our knowledge of many astrophysical properties of the object classes used for distance determination.

2.1. An improved Cepheid distance to the LMC

One of the very promising techniques to derive a truly accurate distance to the LMC (and other nearby spiral and irregular galaxies) is the infrared surface brightness (IRSB) method for Cepheid variables introduced by Fouqué & Gieren (1997). It is a Baade-Wesselink type technique in which a Cepheid's varying surface brightness, as determined from its colour variation during the pulsation cycle, is used to determine its angular diameter variation through the cycle. This information is combined with a knowledge of the variation of its linear diameter which is derived from an integration of its observed radial velocity curve. A linear regression of pairs of angular and linear diameters measured at the same phases yield the distance, and the mean radius of a Cepheid. While the principle of this technique has been known for a long time, its usefulness for distance determination has recently improved dramatically, due to application of the method at infrared wavelengths, first introduced by Welch (1994). Angular diameters calculated from near-infrared colours like V-K are almost an order of magnitude more accurate than those oblained from optical colours, mostly due to two factors: first, the effect of the effective temperature variation of a Cepheid is greatly reduced, at IR wavelengths, compared to its effect on the visual light curve; and secondly, gravity and microturbulence variations in the pulsating atmosphere of a Cepheid, which produce important effects on optical colours, have a negligible influence on infrared colours, which are therefore much better tracers of the Cepheid surface brightness (Laney & Stobie 1995). Gieren, Fouqué & Gómez (1997; GFG97) have shown that the Fouqué & Gieren (1997) calibration of the technique is able to provide distances to individual Cepheids accurate

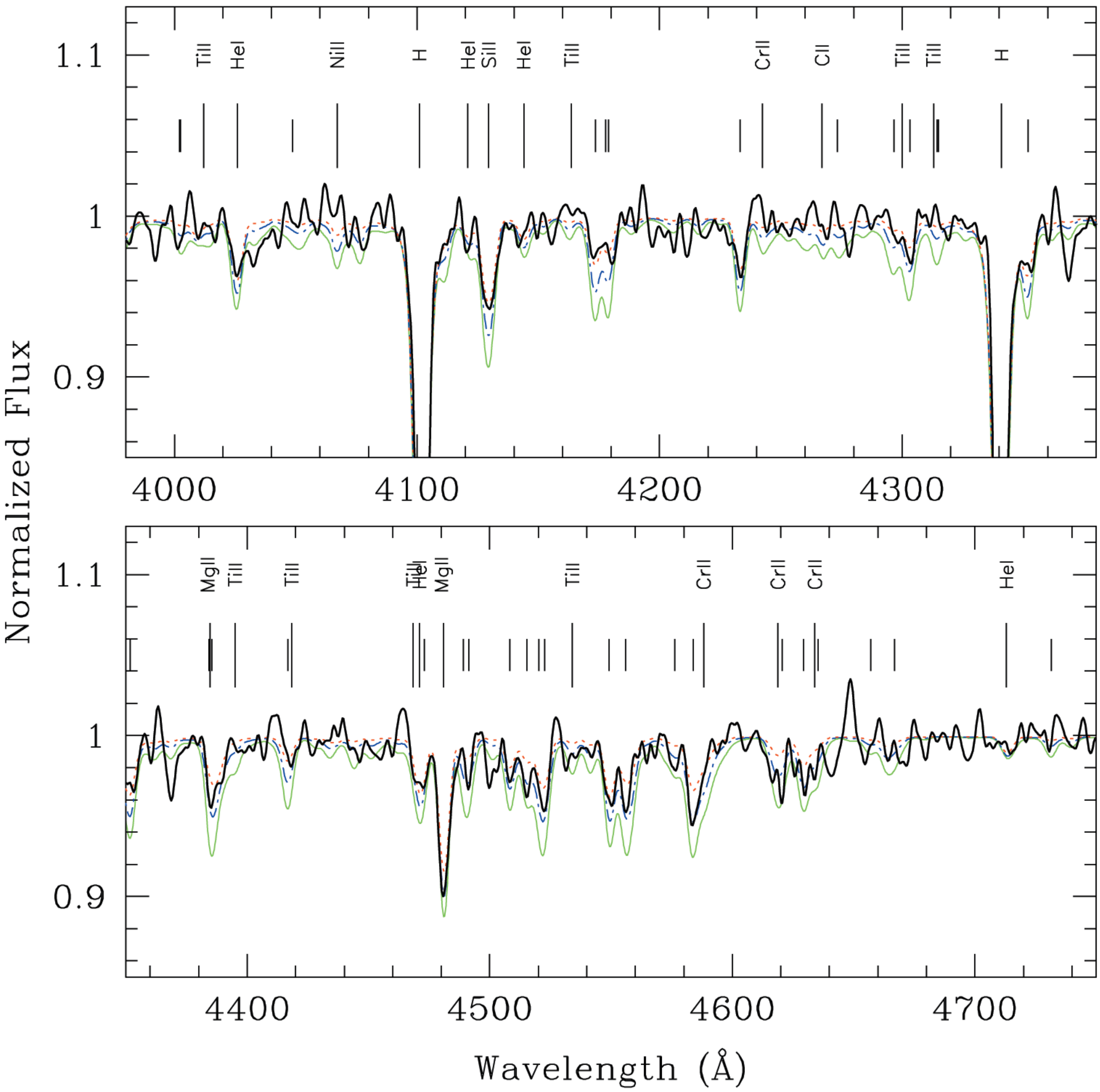

Figure 3: Model fits, corresponding to metal abundances of 0.2, 0.5 and 1.0 solar (red, blue and green curves, respectively), to the spectrum of the B9-A0 supergiant A-8 in NGC 300 (thick black curve). The spectrum was obtained with VLT and FORS1. The metal abundance of this star is about 0.2 solar.

to 4 per cent if the data used in the analysis are of the highest precision. One of the important strengths of the IRSB technique is its very low sensitivity to both reddening and metallicity (GFG97). Also, it is a direct technique which does not require additional, intermediate steps which would introduce additional uncertainties in the distance determination.

In the LMC, the ideal objects on which to apply the IRSB technique are the young, rich clusters, many of which contain substantial numbers of Cepheid variables of similar period and reddening, all at the same distance. We are currently gathering the observational data to carry out IRSB analyses on about a dozen Cepheids in three clusters: NGC 1866, NGC 2031 and NGC 2136/37. First results have been published on the Cepheid variable HV 12198 in NGC 1866, which is the Cepheid "record holder", containing more than 20 Cepheids. For this one object, we have obtained a distance modulus of 18.42, with a total uncertainty of 5 per cent in the distance (Gieren et al. 2000). This value agrees very well with another recent distance determination for NGC 1866 using HST V, I photometry of the cluster main sequence down to V = 25 mag, and ZAMS fitting (Walker et al. 2001), who find 18.35 ± 0.05. Our goal is that at the conclusion of this project (done in collaboration with P. Fouqué (Paris, ESO) and J. Storm (Potsdam)) we will have determined the LMC distance with a remaining uncertainty not exceeding 5 per cent, which would be a giant step towards fixing the zero point of the distance scale. Even further improvement can be expected once we can measure accurate angular diameters of Galactic Cepheid variables directly with VLTI or similar instruments (e.g. Kervella et al. 2001).

2.2. Calibrating the effect of metallicity on Cepheid absolute magnitudes

One of the major uncertainties affecting the distances to galaxies determined from Cepheid period-luminosity (PL) relations is the possibility that

Cepheid absolute magnitudes depend, to a significant amount, on the metallicity. Regarding the size of this effect, empirical tests have led to wildly different claims in the literature over the past few years, from little or no dependence (e.g. Kennicutt et al. 1998; Udalski et al. 2001) to a very strong effect (Allen & Shanks 2001). From theoretical models (Bono et al. 1998; Alibert et al. 1999), even the sign of the metallicity effect is currently under dispute. This shows that there is an urgent need to devise a test capable of giving a precise answer to the problem.

Partly motivated by this open question, about 2 years ago we started a programme with the ESO 2.2-m telescope and Wide Field Imager to carry out a search for Cepheid variables in the Sculptor Group spiral galaxy NGC 300. Given the relative proximity of this galaxy (about 2 Mpc), which allows resolution into stars even in its central regions, its nearly face-on orientation, clear signs of massive star formation, and indications of a substantial metallicity gradient in its disk from previous H II region work, NGC 300 promised to have a large number of Cepheids and to be an excellent target to determine the effect of metallicity on Cepheid luminosities in a similar way as done in M 101 by the HST Key Project team on the the Extragalactic Distance Scale (Kennicutt et al. 1998). Our survey was carried out between July 1999 and January 2000 and has led to the discovery of some 120 new Cepheids, as compared to 16 known from the previous survey of Graham (1984; all his Cepheids were rediscovered by our survey), covering a wide period range from 6 to 115 days (Pietrzynski et al. 2002).

A typical light curve, and the distribution of the Cepheids over the galaxy, are shown in Figures 1 and 2, respectively. In a parallel programme, in collaboration with F. Bresolin and R.P. Kudritzki from the University of Hawaii, we have obtained VLT/FORS multiobject spectra of some 70 blue supergiant candidates in NGC 300 identified from the WFI images, for the purpose of establishing an accurate stellar metallicity gradient in the disk of the galaxy which is needed for the determination of the metallicity effect on Cepheids, and for the independent purpose of improving the use of blue supergiants themselves as standard candles (see next section). More than 60 of our targets were spectroscopically confirmed as blue supergiants, with spectral types ranging from O9 to late A, and first analyses carried out by our team (Bresolin et al. 2002) show that the metallicities determined from the medium-resolution FORS blue spectra (4000–5000 Â) are accurate to about 0.2 dex, and confirm the expected dependence of metallicity on the galactocentric distance (from about solar in the centre to about SMC metallicity in the outskirts of NGC 300). An example of a spectrum is shown in Figure 3.

Once all the spectra have been analysed for their metallicities, using hydrostatic line-blanketed model atmospheres and LTE/NLTE spectrum synthesis, we will proceed with the calibration of the metallicity effect on Cepheid luminosities. Given the amount and quality of the data at our disposal, we are confident that a very accurate result will come from this work.

In yet another, independent approach to this problem we are currently using a sample of metal-poor Galactic outer disk Cepheids, located at galactocentric distances of 12–14 kpc, to determine their distances with the IRSB technique. These metallicity-independent distances will then be compared to those predicted from PL relations calibrated for solar metallicity. Any systematic difference between the two distance determinations should allow us to estimate the effect of metallicity on the absolute magnitudes. A crucial ingredient for this programme to be successful is an accurate knowledge of the metallicities of our target Cepheids. Observing time to obtain these data is scheduled for January 2002 at the ESO NTT. Optical/near-infrared light curves have already been measured from data obtained with the double-channel camera attached to the CTIO YALO telescope, as well as very accurate radial velocity curves (measured with the 1.2-m Swiss telescope on La Silla), which were recently used in a different context to explore the effect of metallicity on the structural properties of Cepheid velocity curves (Pont et al. 2001).

2.3. Blue supergiants as standard candles

The field of extragalactic stellar astronomy is experiencing a time of revival now that the detailed spectroscopic study of single giant and supergiant stars in nearby galaxies has become feasible. Stellar abundance patterns in galaxies can now be studied, and the physical properties of massive stars, in particular those related to their stellar winds, can be used to determine the distances of the parent galaxies. Mass-loss through stellar winds is of fundamental importance in the evolution of stars in the upper H-R diagram. The existence of a relationship between the intensity of the stellar wind momentum and the luminosity of massive stars is a sound prediction of the theory of radiatively driven winds (Kudritzki 1998; Kudritzki & Puls 2000). Briefly, this relationship is summarised as follows:

$$log\ D_{mom} = log\ D_0 + x \cdot log(L/L_\odot)$$

where the modified wind momentum D_{mom} is the product of the mass-loss rate, wind terminal velocity and the square root of the stellar radius. The coefficients D_0 and x must be determined empirically by observations covering blue supergiants (types OBA) of different metallicities. The validity of the Wind Momentum-Luminosity Relationship (WLR) has been demonstrated empirically by Puls et al. (1996) for O-type stars in the Galaxy and the Magellanic Clouds, as well as for supergiants of type B and A in the Milky Way (Kudritzki et al. 1999), M 31 (McCarthy et al. 1997) and M 33 (McCarthy et al. 1995), confirming the expected dependence of the relation on spectral type.

What makes the WLR appealing as an extragalactic distance indicator is the extreme brightness of blue supergiants (up to $M_V = -10$ for A-type supergiants). The basic approach consists in deriving the stellar parameters (temperature, gravity and metallicity) from optical spectroscopy, and modelling the $H\alpha$ line profile to obtain the wind properties (mass-loss rate and terminal velocity). The intrinsic luminosity, and hence the distance, follows from an empirically calibrated WLR, and the knowledge of the stellar apparent magnitude, reddening and extinction. With 8-m-class telescopes, the necessary spectroscopic observations can be carried out to distances of 10–15 Mpc. Previous work of Kudritzki et al. (1999) indicates that the WLR has the potential to yield distances with an accuracy rivalling that of the Cepheid PL relationship. It is also currently the only stellar distance indicator allowing a distance determination on the grounds of spectroscopic analysis alone (but apparent magnitudes and extinction must, of course, be measured from photometry). However, the dependence of the WLR on spectral type and metallicity must first be explored in greater detail before blue supergiants can be used as a new class of accurate, far-reaching stellar distance indicators.

In an effort to obtain such improved calibrations, we have taken VLT/FORS spectra in the blue spectral range of some 60 blue supergiants in NGC 300 to determine their abundances and the systematic stellar abundance variations over the disk of this galaxy. Very recently, we were able to complement these data with red spectra covering the $H\alpha$ line, from which the wind properties of the stars will be determined. From these data, we will be able to populate the WLR diagram, explore in detail its dependence on metallicity and spectral type, and set a zero point to the WLR from the extensive Cepheid sample we have discovered in NGC 300. A first, very encouraging example of a WLR analysis of one of the blue supergiants in NGC 300 is shown in Figure 4 (for more details, see Bresolin et al. 2002).

To improve the Cepheid distance determination beyond what is possible with optical photometric data, we are planning to carry out K-band photometry of the Cepheids, which will allow us to get rid of the problem of reddening and absorption internal to the galaxy. We expect that our current programme on NGC 300 will produce decisive progress for the calibration of the blue supergiant WLR for distance determination, and that subsequently we can use this new tool to derive accurate distances to a number of galaxies out to the Virgo and Fornax clusters.

2.4. The ARAUCARIA project

In addition to performing studies intending to improve Cepheids and blue supergiants as standard candles, we have started a more general programme (called the ARAUCARIA project, after the Chilean national tree, which is common in our southern location) to test the influence of environmental properties of galaxies on a number of other stellar distance indicators. These include RR Lyrae variables, red clump stars (which are currently the only stellar distance indicators which can be geometrically calibrated from HIPPARCOS parallaxes), and planetary nebulae (PN). Our strategy is to obtain and compare distances from all the different stellar candles in a common set of nearby, resolved galaxies which show a wide range of environmental properties. Our work on NGC 300 is a first example of this kind of work. In this particular galaxy we have, in addition to the work mentioned in previous sections, obtained deep narrow-band and *H*α photometry with the ESO 2.2-m telescope Wide Field Imager (in collaboration with R. Méndez, Munich, and R. P. Kudritzki, Hawaii) which will allow us to detect and measure its complete population of PN down to the faintest objects, and to check any possible dependence of the Planetary Nebulae Luminosity Function (PNLF) on the stellar population producing the PN (NGC 300 shows recent star formation, as opposed to the bulge of M 31, which has been the principal calibrator of the PNLF method in the past). To this end, we will use our new accurate Cepheid distance to NGC 300 to set the zero point of the narrow-band fluxes.

Studies of red clump stars in the near-infrared K band, where age and metallicity effects on absolute magnitudes are expected to be less important than for I-band magnitudes (Alves 2000), are underway in the LMC, SMC and several Local Group dwarf galaxies. We also plan to test the red clump star method in NGC 300 in the near future. As an outcome of the ARAUCARIA programme, we not only hope to set the zero point of the extragalactic distance scale with exquisite accuracy, but we are also confident that a wealth of new astrophysical information about the object classes studied (and individual, particularly interesting objects) will turn up along the way.

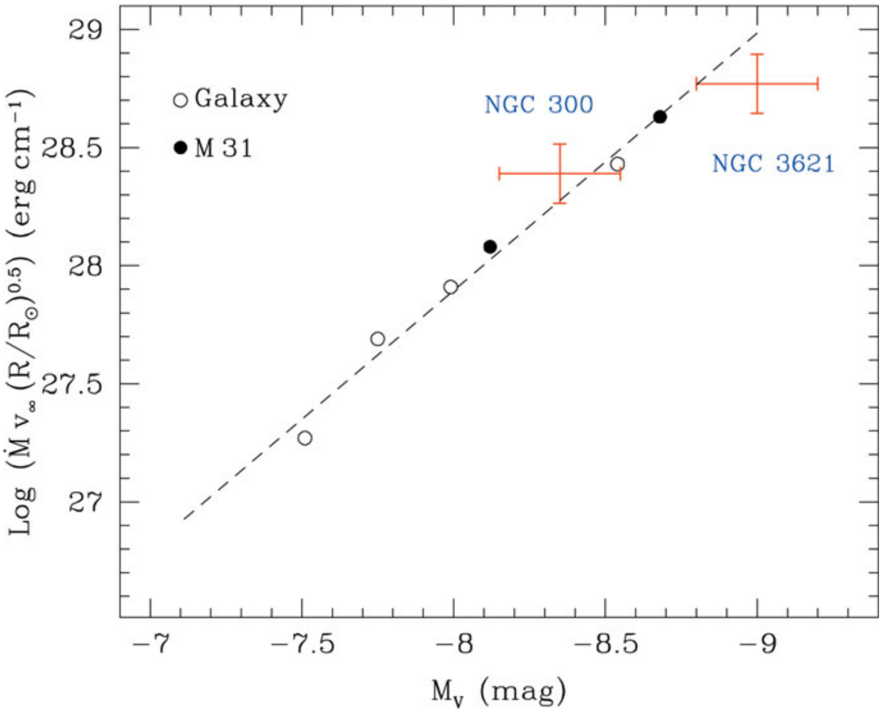

Figure 4: Wind momentum-luminosity relationship for A supergiants, from Galactic (open circles) and M 31 (filled circles) stars (data sources: see text). Also plotted is the A0 supergiant in NGC 3621 analysed by Bresolin et al. (2001), and the A0 supergiant D-12 in NGC 300 analysed by Bresolin et al. (2002).

3. Globular Clusters and Galaxy Formation

One of the major goals of modern astronomy is an understanding of galaxy formation. What caused the variety of galaxy types we see today? What were the conditions at the time of their formation? When did galaxies form? The crude answer to this last question is, unfortunately, generally very long ago, making it very difficult to investigate this topic by simply observing galaxies which are currently forming. Thus, we must turn to other clues to reveal the distant past.

Globular clusters (GCs) are ideal tools for studying the earliest epochs of galaxy formation, given that they are the oldest easily-dated objects present in all but the least massive galaxies and that they are also among the brightest objects in galaxies, especially giant elliptical galaxies, where they are present in very large numbers over a wide radial range, and thus readily accessible for detailed observations.

3.1. An observational study of galaxy formation using globular clusters

The use of GCs to study galaxy formation beyond the Milky Way has boomed in the last decade. The primary catalyst has been the discovery of multiple (typically 2) distinct subpopulations of GCs in a given galaxy (e.g. Whitmore et al. 1995, Geisler et al. 1996). Such multimodality provides clear evidence for distinct GC, and therefore galaxy formation epochs and/ or processes. Ashman and Zepf predicted bimodality in their 1992 paper on the formation of globular clusters in gaseous mergers. These results have inspired a host of other observational studies (e.g. Gebhardt and Kissler-Patig 1999, Kundu and Whitmore 2001) as well as stimulated a number of theoretical papers suggesting new galaxy formation models and provided the observational constraints used as their input (e.g. Forbes et al. 1997, Côté et al. 1998). This was one of the key topics at the recent IAU Symposium 207 on “Extragalactic Star Clusters” held in Pucon, Chile, in March. This meeting drove home the point that GCs have much to teach us about the formation of galaxies. This was the first ever IAU Symposium in Chile and we note with pride that our Astronomy Group co-organised and hosted this very successful meeting.

Globular clusters provide a wide variety of evidence useful to our quest. Particularly important are metal abundances and kinematic data for a large number of GCs in a galaxy over its entire extent. Such information can help to tightly constrain galaxy formation models. However, the observational requirements for such a study are quite demanding: one needs accurate (~ 0.2 dex) metal abundances and/or radial

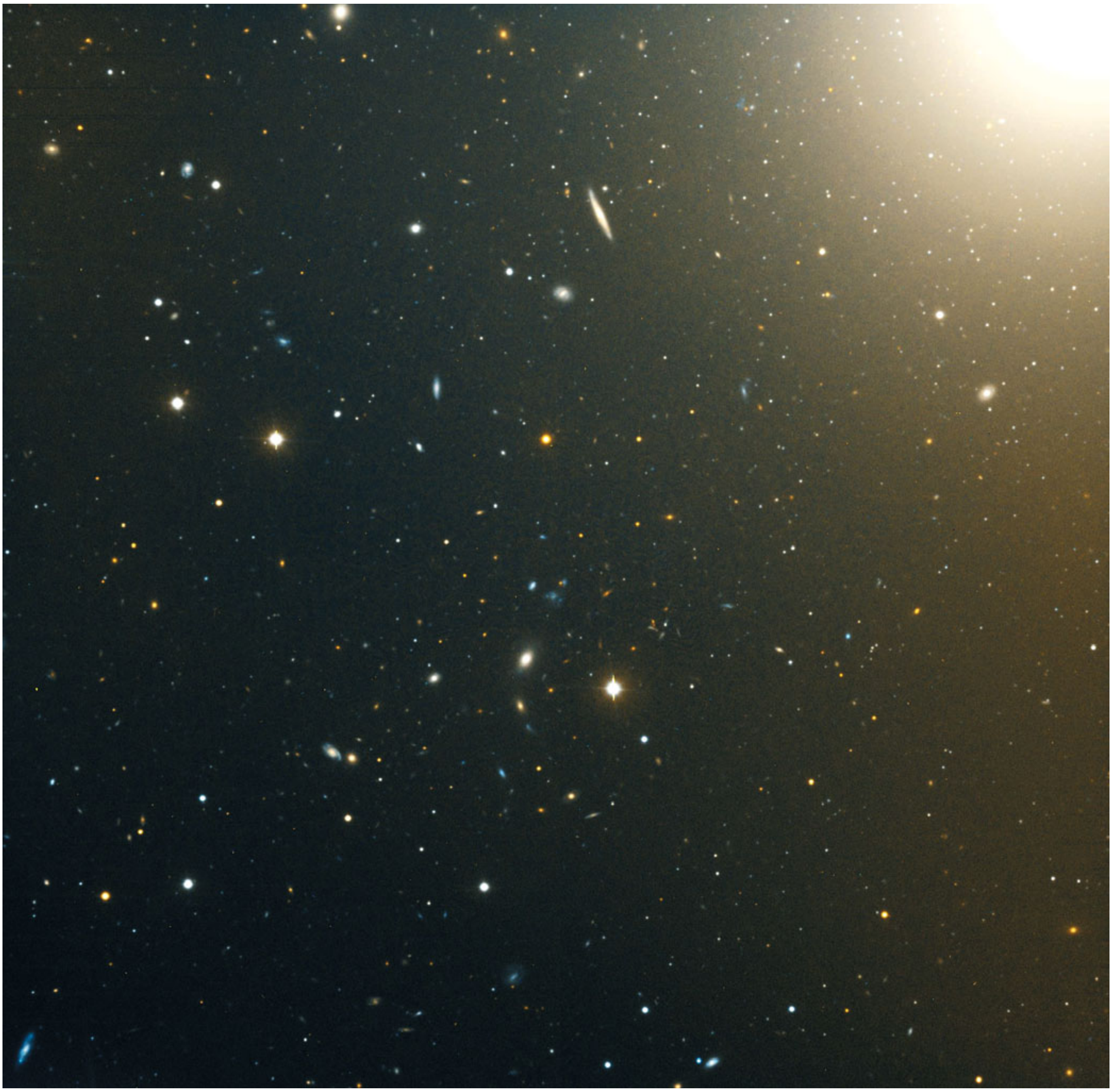

Figure 5: The north-east region of NGC 1399, imaged with FORS2 in V and I and an exposure time of 300 s. The rich cluster population is discernable, as well as many galaxies in the field. This image has been obtained during a spectroscopic run with FORS2 and MXU, during which about 500 spectra of clusters were collected.

velocities ($\lesssim$ 50 km/s) for hundreds of clusters to build up a statistically significant sample to be able to resolve distinct metallicity peaks or discern kinematic differences between any subpopulations. In addition, one needs large spatial coverage within a galaxy to check for any radial trends, which can yield additional constraints on formation models. Such knowledge is only now beginning to become available. We present here some of our recent work along these lines.

3.2. Photometry and Spectroscopy of the Globular Cluster System of NGC 1399

NGC 1399, the central cD-galaxy in the nearby (~ 19 Mpc) Fornax cluster, plays a leading role in the study of extragalactic GCs. Its rich GC system has frequently been the target of investigators (see Kissler-Patig et al. 1999 and references therein), but the most fundamental questions are either still open or under debate. Even the question as to what degree the richness of its cluster system is extraordinary is not conclusively answered because of the huge extension of both the cD-halo and the GC system, which makes the total number of clusters as well as the total luminosity of NGC 1399 difficult to measure. In some previous work, the substructure of its GC system has been recognised (Ostrov et al. 1998), however, without detailing the photometric, spatial and kinematic properties of subpopulations of clusters. The pronounced bimodal colour distribution, and thus very likely also metallicity distribution, suggests a first order distinction between metal-poor and metal-rich clusters, although it is not excluded that the composition may be more complex. We therefore ask: Are metal-rich and metal-poor clusters differently distributed in space? Do their properties correspond to the properties of the underlying field population? Are there kinematical differences and how can they be interpreted in a dynamical context? Finally, what could be a scenario which explains all properties of the GC system?

The two main factors, which make our new photometric data set superior are the use of the Washington system (in fact, we use Washington C and Kron-Cousins R) with its excellent

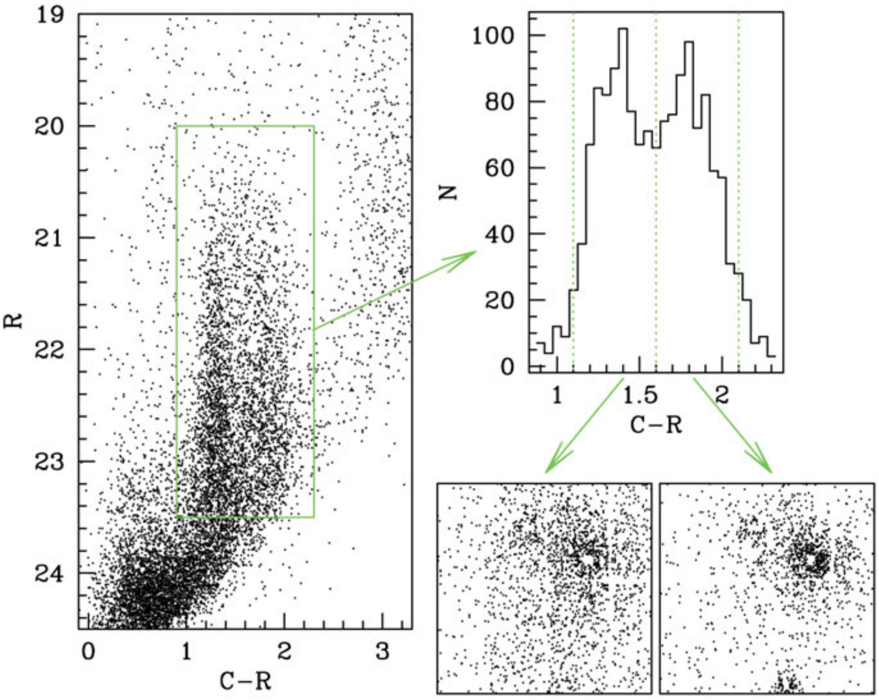

Figure 6: The left panel is the R-(C-R) CMD of all point sources found in the MOSAIC field. The bimodal colour distribution is clearly visible, again demonstrated in the C-R histogram (upper right panel). The lower right panel shows the distribution of blue clusters (left) and red clusters (right) in the 36 × 36 arcmin field. The red clusters are distinctly more concentrated towards NGC 1399. Also NGC 1387 at the lower margin and NGC 1404 left of NGC 1399 are visible, which cannot be seen in the distribution of blue clusters.

metallicity resolution and a large field of 36 × 36 arcmin, which we achieved with the MOSAIC camera of the 4-m telescope at Cerro Tololo. In combination with new and unique spectroscopic data from the VLT we now have the most powerful data set ever oblained for a GC system of an early type galaxy.

Figure 5 shows the north-east region around NGC 1399. The colours have been constructed using V and I exposures from FORS2 at Kueyen, which we took in the course of our spectroscopic run (see next section). The richness of the cluster system is apparent, as is the rich background population of galaxies, which particularly in bad seeing can strongly contaminate a list of GC candidates.

The bimodality of the colour distribution shows up nicely in Figure 6, which is the R vs. (C-R) colour-magnitude diagram of all unresolved objects found on the wide-field images. Since the photometric completeness is controlled by the C images, we have a sharp, inclined completeness limit. The bulk of the faint blue objects are mostly galaxies, which in a V vs. (V-I) diagram merge with the blue GC population and thus contribute significantly to the background contamination. The right panel is a colour histogram of those objects within the rectangle drawn in the CMD, which delimits the expected domain of the brighter half of the GCs. In the plot of the area distributions of blue and red clusters, one notes the much stronger concentration of red clusters toward their host galaxies. Even two neighbouring galaxies, NGC 1404 and NGC 1387, are discernible by the distribution of red clusters, which are not visible if only the blue clusters are plotted.

To be more quantitative, we plot the surface density profile vs. the radial distance for the red and the blue clusters, as well as for the galaxy light in the C and R bands (Fig. 7). The zero-points of the ordinate for all four components have been shifted to make the differences between them best visible. The radial range covered is larger than in any other previous CCD study. We see that in the outermost region the blue and red cluster profiles cannot be distinguished, but the blue cluster profile becomes progressively shallower than that of the red cluster inwards. This difference is also reflected in the galaxy light profile, where the colour gradient becomes best visible between 3 and 10 arcmin. In fact, the galaxy colour gradient resembles nicely the ratio of red to blue clusters at any given radius, so the galaxy "knows" about its bimodal cluster population. We stress that this is very difficult to see in a field smaller than ours. The fact that the galaxy colour profile follows that of the ratio of red to blue clusters is a strong point against any "stripping" scenario, in which the rich cluster system has been built up by stripping globulars from neighbouring galaxies and argues for a scenario in which the field population forms together with the cluster population. We note that we are also investigating the GC luminosity function and its utility as a distance indicator, with particular attention to the metallicity dependence of the turnover.

With the advent of large telescopes like the VLT in combination with a sophisticated and efficient multi-object spectroscopic device like the Mask Exchange Unit (MXU) at FORS2, spectroscopy of objects as faint as V = 23.5 for measuring radial velocities has become feasible. As for the investigation of GC systems of early-type galaxies, two important objectives can now be addressed: firstly, the kinematical be-

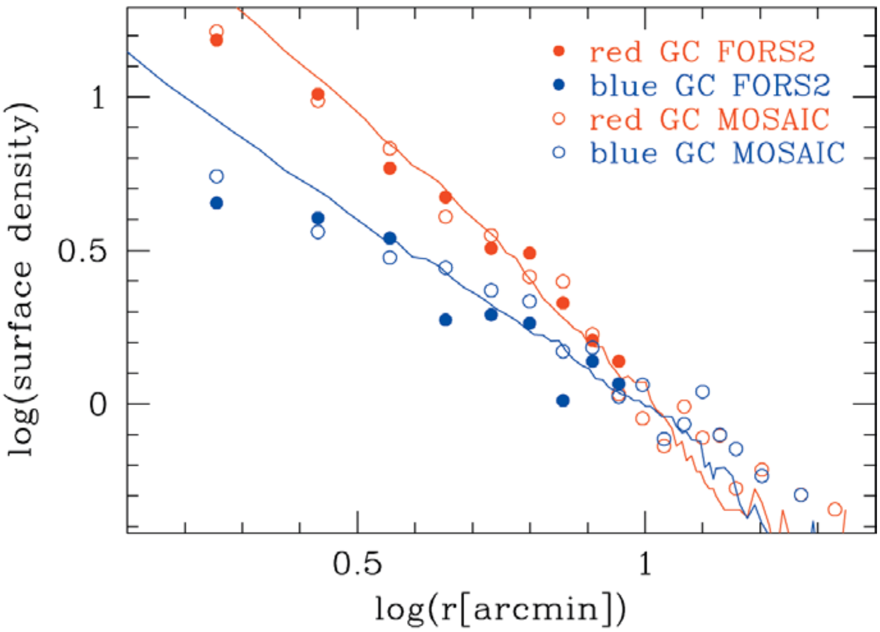

Figure 7: This plot shows the surface density profiles of the radial distribution of red and blue clusters, measured on FORS2 images (filled circles) and MOSAIC images (open circles). The solid lines are the galaxy light profiles in the C filter (blue) and the R filter (red). The zero-points of all four components have been shifted to make the differences most visible. The colour gradient in the galaxy light can be seen best between 0.5 < logr < 1.

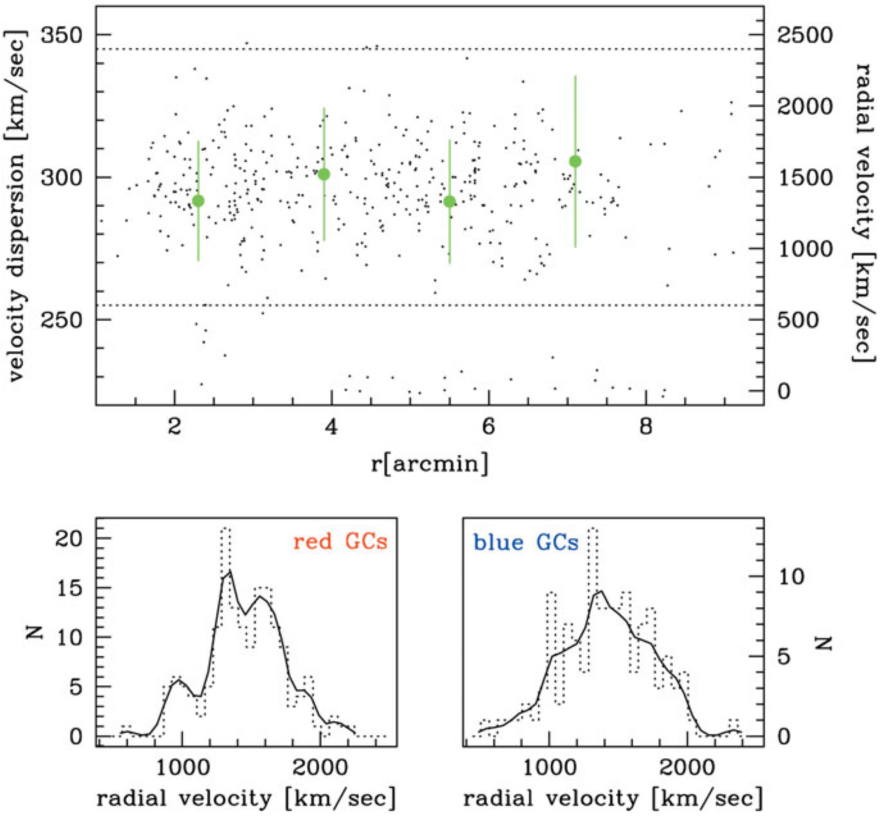

Figure 8: The upper panel is a combination of two figures. The small points are all measured clusters with their velocities (right ordinate) plotted vs. their projected galactocentric distances. The dashed lines indicate the velocity limits which have been applied for calculating the velocity dispersions. The large points are the projected velocity dispersions (left ordinate) in four radial bins with their uncertainties indicated. The lower left panel shows the velocity distribution of the red clusters, the right panel that of the blue clusters. One can see the smaller velocity dispersion of the red clusters, but also that these histograms are not very well approximated by Gaussians. The curves are the result of smoothing the data.

haviour of distinct subpopulations of GCs, and secondly, the use of GCs as probes for the gravitational potential of the host galaxy. Radial velocities of GCs have already been measured for some galaxies (NGC 1399, M87, NGC 4472) using the Keck and 4-m-class telescopes (Kissler-Patig et al. 1999, Cohen et al. 1998, Côté et al. 2001, Zepf et al. 2001), but the VLT vastly improves the situation in terms of accuracy and number statistics. Large sample size is particularly essential for a dynamical analysis, because about 400–500 probes are necessary to disentangle the phase space distribution and the potential (e.g. Merrit 1993).

We therefore started a programme aimed at getting a large sample of GC radial velocities around elliptical galaxies. The first natural target in the southern sky is NGC 1399. In December 2000, we observed with FORS2 and MXU at Unit 2 various fields around NGC 1399. The pre-selection of GC candidates was performed with the aid of our MOSAIC Washington photometry. As the radial velocities showed later on, the distinction of clusters from background galaxies and foreground stars worked excellently, giving a contamination fraction as low as 5%. We used the grism 600B, with which the arc lines have a FWHM of 5 Å. The spectral coverage was from about 3800 Å to 5800 Å, depending on the slit position on the mask. In total we observed 13 masks with varying exposure times between 45 and 90 min. The cluster candidates had R-magnitudes between 20 and 22.5 mag.

The surface density of targets, particularly at small projected galactocentric radii, is very high. Therefore, we decided not to measure the sky through the same slit as the object, but to set independent sky slits, which greatly improved the flexibility of object selection. In that way we could fill one mask with more than 100 slits. The Mask Manufacturing Unit works sufficiently accurately to allow a satisfactory sky subtraction of independent object and sky slits.

The observations resulted in about 500 spectra of cluster candidates together with 300 miscellaneous objects, including galaxies, stars, and clusters which fell outside our photometric selection criteria, which were observed intentionally to take advantage of available slit positions when good GC candidates were not available. We have measured radial velocities for about 450 clusters by both cross-correlation techniques and direct measurements of line positions. The uncertainty for most objects is in the range 20–50 km/s. The final sample will probably contain about 450 GC velocities, which is the largest sample of dynamical probes ever obtained for an early-type galaxy.

Figure 8 (top) shows both the individual velocities and the velocity dispersion (right and left ordinates) and their radial dependence. Because the work is still in progress, we can only give preliminary results. We do not see any significant rotation for most of the cluster population except perhaps for the outer metal-poor clusters, for which a marginal rotation signature might be present. Considering the entire sample, the projected velocity dispersion seems to be constant with radial distance and has a value of 310 ± 20 km/s.

We use a colour of C – R = 1.4 to separate the metal-poor from the metal-rich clusters. The metal-poor and the metal-rich subsamples show slightly different velocity dispersions of 330 ± 18 km/s and 291 ± 16 km/s, respectively, and again do not indicate a change with radial distance (Fig. 8, bottom).

Although the proper dynamical analysis still has to come, a few interesting remarks can already be made. If we assume spherical symmetry, we may apply the spherical Jeans equation (e.g. Binney & Tremaine 1987):

$$\frac{G \cdot M(r)}{r} = -\sigma_r^2 \cdot \left(\frac{d\ln\rho}{d\ln r} + \frac{d\ln\sigma_r}{d\ln r} + 2\beta\right)$$

where G is the constant of gravitation, r the galactocentric distance, M(r) the mass contained within r, σ_r is the radial component of the velocity dispersion, $\rho(r)$ the density profile of clusters, $\beta = 1 - \frac{\sigma_\Theta^2}{\sigma_r^2}$ with σ_Θ being the tangential velocity dispersion. Unless β is non-zero, a radially constant *projected* velocity dispersion implies a constant σ_r and $\frac{d\ ln\sigma_r}{d\ ln\ r} = 0$. Within our radial range, the red and the blue clusters show different density profiles (Dirsch et al. 2001), $\frac{d\ ln\rho}{d\ ln\ r} \sim -2.5 \pm 0.1$ and -1.8 ± 0.1, respectively. The difference of the density profiles could account completely for the difference in the velocity dispersions, if β would be zero.

A handy formula for the mass inside a radius r is ($\beta = 0$)

$$M[M_\odot] = 2 \cdot 10^{10} \cdot r[kpc] \cdot \left(\frac{\sigma_r^2}{300km/s}\right)^2 \cdot \alpha$$

where α is the logarithmic slope of $\rho(r)$ and where a distance of 19 Mpc has been assumed. The mass inside 10 kpc is $4.2 \cdot 10^{11}\ M_\odot$ and inside 40 kpc $1.7 \cdot 10^{12}\ M_\odot$, which is in good agreement with the values given by Jones et al. (1997) based on X-ray analyses and indicates that isotropy is not grossly violated. We note that we are performing a detailed investigation of the mass and M/L distribution in NGC 1399 based on these data, in collaboration with K. Gebhardt (University of Texas), D. Minniti, L. Infante, M. Rejkuba (Universidad Católica), J.C. Forte (Universidad La Plata), M. Hilker (Universität Bonn), S. Larsen (Lick Observatory), V. Alonso (Cordoba Observatory), E. Grebel (MPIA Heidelberg). A progress report has been given in Richtler et al. (2001).

3.3. What can this study teach us about Galaxy Formation?

NGC 1399 possesses roughly three times as many GCs per unit galaxy luminosity as is "normal" for an early-type galaxy, a property that is shared with other central galaxies in clusters. There have been numerous attempts to interpret this finding, ranging from the concept of a universal GC formation efficiency (McLaughlin 1999) to cluster formation in mergers (Ashman & Zepf 1992) and infall of dwarf galaxies (Hilker et al. 1999; Côté et al. 1998). Here we want to give a few remarks regarding our present view of NGC 1399 and its cluster system.

There is evidence that (for whatever reason) the efficiency of GC formation increases with the star formation rate (Larsen & Richtler 2000), which is also supported by the rich young cluster systems in present-day mergers (Whitmore & Schweizer 1995). The centre of a galaxy cluster obviously is a favourite place for rapid and perhaps multiple merger events. A multiple merger at early times in which gas-rich and chemically unevolved disk galaxies participated is an attractive framework for explaining the properties of NGC 1399. In this scenario, most of the clusters, both metal-rich and metal-poor, could have formed already in the premerger phase, either as halo/bulge/disk clusters of the involved spiral galaxies well before the actual merger took place or during the starburst, which probably accompanied the early merger phases, when the galaxies are still detached. This is suggested by the declining amount of molecular gas in evolving present-day mergers (Gao & Solomon 1999). After the merger the remaining gas rapidly falls towards the centre (Barnes & Hernquist 1996) and forms stars and preferentially metal-rich clusters, which mix with the already existing cluster population and cause a steeper concentration of metal-rich clusters. If "normal" elliptical galaxies in low-density regions are formed by the merging of typically two disk galaxies with already moderate gas fractions, one may not expect a very high specific frequency. NGC 1316 (Fornax A) may be considered as an example (Gómez & Richtler 2001, Goud frooif et al. 2000) for such a merger. In the case of the central cD, NGC 1399, the much higher specific frequency may be due to a much higher gas fraction and deeper potential well, which makes it harder for the gas to escape, and thus forced a higher gas fraction to be involved in violent star formation processes.

Within such a scenario, one would expect to find the same radial colour gradient in the galaxy light as is seen in the clusters, just as we observe. The difference in the velocity dispersions of red and blue clusters simply reflects the difference in the density profiles. Also almost isotropic orbits are expected, if the majority of blue and red clusters already existed before the merger remnant achieved its present dynamical state. Our programme for the future is to look at other early galaxies with rich cluster systems where we can obtain data similar to that in hand for NGC 1399. The most attractive candidates are NGC 5128 (Centaurus A) where it will be possible to observe the majority of its GCs, and NGC 4636, a relatively isolated galaxy located at the southern extension of the Virgo cluster, which nevertheless has an unusually rich cluster system. The VLT and forthcoming VIMOS will provide an unrivalled combination for this endeavour.

Finally, we would like to extend a warm invitation to those astronomers ready to take a few extra hours on their next trip to Chile to see our place, talk to our people and, if possible, give a seminar about their research.

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