Measuring Improved Distances to Nearby Galaxies: The Araucaria Project

Wolfgang Gieren[1]
Grzegorz Pietrzynski[1]
Fabio Bresolin[2]
Rolf-Peter Kudritzki[2]
Dante Minniti[3]
Miguel Urbaneja[2]
Igor Soszynski[1]
Jesper Storm[4]
Pascal Fouqué[5]
Giuseppe Bono[6]
Alistair Walker[7]
José García[1]

[1] Universidad de Concepción, Chile
[2] Institute for Astronomy, Hawaii, USA
[3] Universidad Católica, Chile
[4] Astrophysikalisches Institut Potsdam, Germany
[5] Observatoire Midi-Pyrénées, France
[6] Osservatorio Astronomico di Roma, Italy
[7] Cerro Tololo Inter-American Observatory, Chile

Figure 1: The spiral galaxy NGC 55 in the Sculptor Group, one of the target galaxies of the Araucaria Project. The presence of an abundant young stellar population is revealed by the many blue objects concentrated towards the disc of this galaxy.

An intense use of ESO telescopes over the past years has allowed us to make significant improvements in the characterisation of stellar populations, and in the determination of the distances of nearby galaxies. We report on recent progress on the use of Cepheid variables and blue supergiant stars for the accurate measurement of galaxy distances. This work will finally lead to a significant reduction of the uncertainty on the Hubble constant, which measures the current rate of expansion of the Universe.

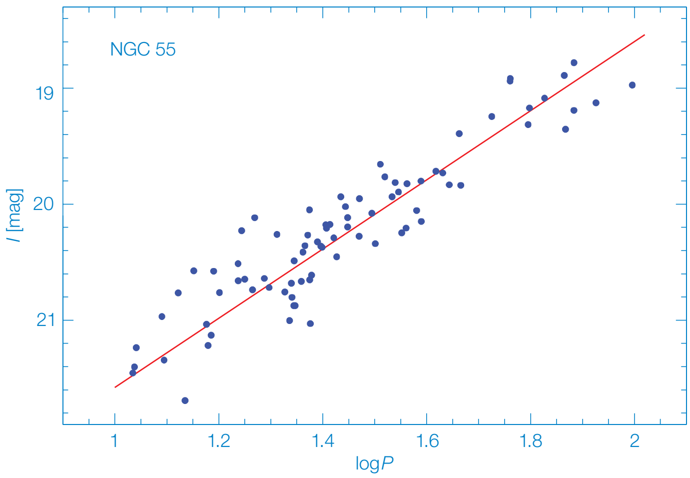
The measurement of distances to astronomical objects is a fundamental problem ever since humanity began to look at the stars. Knowledge of precise distances to galaxies is important for the study of a broad range of astrophysical phenomena, including the true energy outputs of luminous sources; it is also fundamental for establishing accurate cosmological parameters which describe the actual state, and history of the Universe. One parameter of particular interest is the Hubble constant H_0 which measures the current acceleration of the expanding Universe. Some ten years ago, the *HST Key Project on the Extragalactic Distance Scale* (Freedman et al. 2001) set out to measure Cepheid distances to a sample of nearby galaxies in order to calibrate far-reaching secondary methods of distance measurement which could be used to determine the distances to galaxies remote enough to find an unbiased value of H_0. Their very successful work was hampered by the fact that Cepheid variables are not a perfect instrument for distance measurement. Cepheids, like other stellar standard candles, are affected to some degree by the environmental properties of their host galaxies, most notably abundances of the heavy elements, and the ages of the stellar populations. Such effects must be taken into account if truly accurate distances to nearby galaxies are to be measured. With this motivation in mind, our group set out, a few years ago, to thoroughly investigate the environmental dependences of a number of stellar distance indicators, including Cepheids, blue supergiants, RR Lyrae stars, red clump giants, and the tip of the red giant branch (TRGB) magnitude in the *Araucaria Project (http://ifa.hawaii.edu/~bresolin/Araucaria/)*. This project is a necessary complement to the *HST Key Project*. Over the past two years, the Araucaria Project has obtained a *Large Programme* status at ESO, and a number of important scientific results have emerged from the abundant data obtained with ESO telescopes, some of which we will briefly describe in this article. In this progress report, we will focus on two types of distance indicators, the pulsating Cepheid variables, and the extremely luminous blue supergiant stars.

Progress on the Cepheid period-luminosity relation

The radially pulsating and relatively cool Cepheid supergiant stars exhibit a well-known relation between their mean intrinsic luminosity, and their pulsation periods – *the famous period-luminosity* (PL) *relation*, which is normally written in the form $M = a \log P + b$, where M is the mean absolute magnitude (in a given photometric band), and P the period (in days). With the PL relation calibrated, the mean luminosities of Cepheids, and thus their distances, can be inferred from their periods. In order to determine the dependence of the PL relation on metallicity, we have been conducting surveys for Cepheids in a number of spiral and irregular galaxies of widely different metallicities in the Local Group, and in the Sculptor Group. From a comparative study of the PL relations exhibited by the Cepheids in the different galaxies, in a variety of optical and near-infrared photometric bands, we can expect to determine both, the effect of metallicity on the *slope*, and on the *zero point* of the PL relation, and to filter out the most appropriate photometric band for distance work in which the effect is minimised.

So far, we have completed optical (BVI) surveys for Cepheids over the whole spatial extents for the Local Group galaxies NGC 6822 (Pietrzynski et al. 2004), NGC 3109 and WLM; these data complement previous surveys for Cepheids in other Local Group irregular galaxies (LMC, SMC, and IC 1613). In Sculptor, Cepheid surveys have been completed for the spiral galaxies NGC 300 (Gieren et al. 2004), NGC 55, NGC 247, and NGC 7793. The wide-field imaging data used in these surveys were obtained at the ESO 2.2-m telescope and WFI instrument, with a strong complement from the Polish 1.3-m telescope and mosaic camera at Las Campanas Observatory, and the 4-m Blanco telescope and mosaic camera at CTIO. In all Araucaria target galaxies, including those in the Local Group, we were able to very substantially enlarge the number of known Cepheids, and in particular find long-period ones which carry the strongest weight in the distance determinations. In three of the four Sculptor Group spiral galaxies, we have discovered the first Cepheid variables ever. An example is NGC 55 (Figure 1); in this galaxy, we have detected 81 Cepheids with periods in the range 10–100 days which define a tight PL relation (Figure 2). In Figure 3, we show the light curves of two of these variables in the *V*- and *I*-bands, obtained from our mosaic images taken on about 50 different nights. As an example of the improvement on the Cepheid census in the Local Group, we show in Figure 4 (see next page) the PL relation defined by some 100 Cepheids in NGC 3109, most of them discovered in the Araucaria Project from data taken during 80 nights at the Polish 1.3-m telescope on Las Campanas. In contrast to the more massive spiral NGC 55, NGC 3109 does not contain a population of very long-period Cepheids.

Figure 2: The Cepheid period-luminosity relation defined by Cepheid variables in NGC 55, in the *I*-band. The period P is in days. From wide-field images taken on about 50 different nights, we discovered 81 Cepheids with periods longer than 10 days – these are the first Cepheid variables ever discovered in this galaxy. Differential reddening in this rather inclined galaxy is likely to contribute significantly to the observed scatter. This effect should be greatly reduced in the near-infrared PL relations we are currently measuring from VLT/ISAAC images.



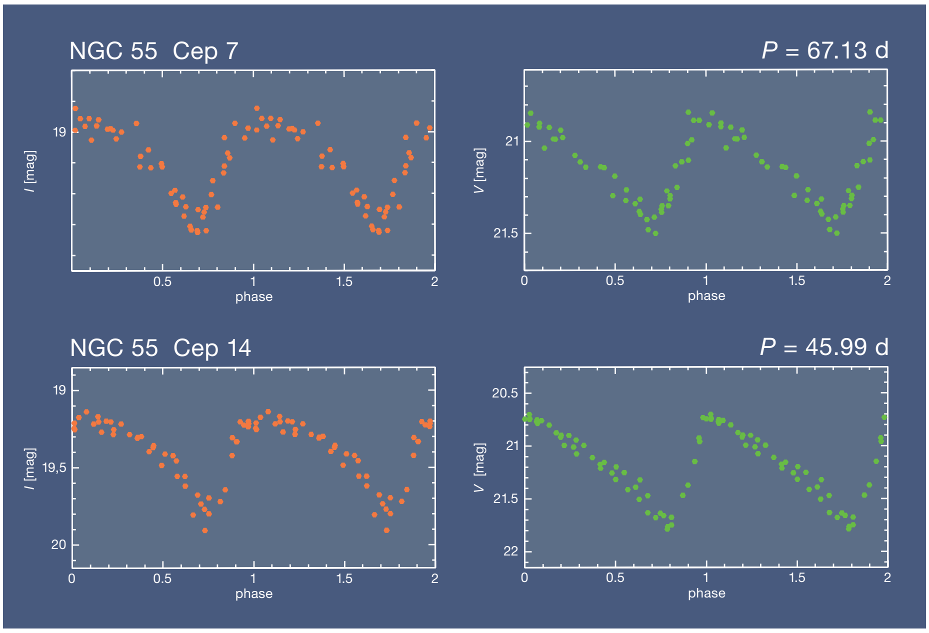


Figure 3: Phased light curves in *V*- and *I*-bands for two of the Cepheids we discovered in NGC 55. The periods are indicated on the plots. Such data lead to a very precise determination of the mean magnitudes of the variables.

One first conclusion from these data is that in the optical V and I bands, the slopes of the PL relations observed in all these different galaxies are consistent with the slopes defined by the LMC Cepheids observed in the OGLE-II Project (Udalski 2000), arguing for a very small metallicity effect (consistent with a null effect) on the PL relation *slope* in the [Fe/H] range from about – 1.0 dex to – 0.3 dex, spanned by the young populations of our target galaxies. Recently, our distance work on LMC and Milky Way Cepheids with the direct Baade-Wesselink-type *infrared surface brightness technique* (Gieren et al. 2005a) has furthermore provided strong evidence that the slope of the PL relation keeps being independent of metallicity up to the solar abundance shown by the Milky Way Cepheids. This is an especially important result since many of the massive spiral galaxies in the HST Key Project have near-solar heavy-element abundances. Application of the LMC Cepheid slopes in V and I to the observed Cepheid PL relations in such

Figure 4: The Cepheid PL relation in the *I*-band for the Local Group galaxy NGC 3109. Most of the Cepheids in this plot were discovered in the Araucaria Project. Note that NGC 3109, in contrast to NGC 55, does not contain truly long-period Cepheids – the longest observed period is 31 days.

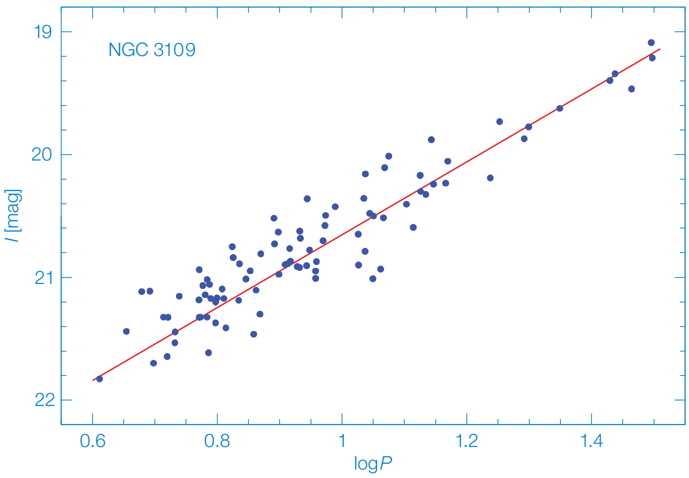
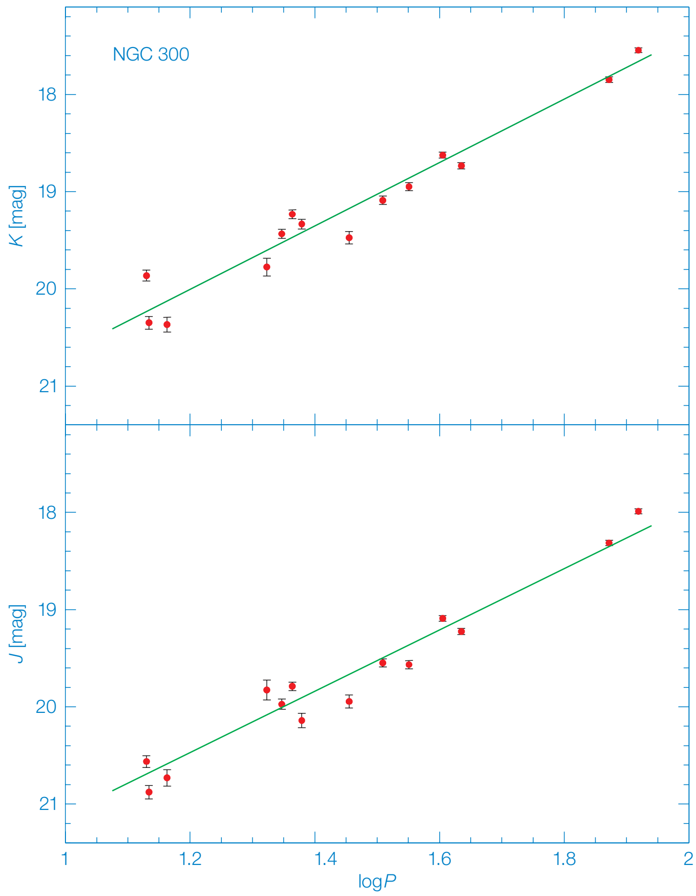


Figure 5: The near-infrared PL relations in *J*- and *K*-bands determined from VLT/ISAAC data for Cepheids in the Sculptor galaxy NGC 300. The variables were previously discovered by Pietrzynski et al. (2002) from wide-field images obtained at the ESO-MPI 2.2-m telescope. Each Cepheid was observed at two different epochs and its mean magnitude determined with the method of Soszynski et al. (2005). The data fit very well the PL relations in *J* and *K* as obtained for the LMC Cepheids by Persson et al. (2004). The slopes of the solid lines were taken from this work.



galaxies should therefore not cause any important systematic problem.

Very recently (Bresolin et al. 2005a), we have been testing the effect *blending* of Cepheids with nearby projected neighbour stars in the crowded images of distant galaxies has, by comparing ground-based photometry of Cepheids in NGC 300 from ESO-WFI data to BVI images of the same Cepheids obtained with the Hubble Space Telescope and ACS. In the case of NGC 300, with its distance of close to 2 Mpc, the systematic effect of blending on the distance derived from the ground-based images is found to be only ~ 2 per cent. The main reason is that long-period Cepheids are intrinsically bright enough to outshine nearly all of the close companions on the images, making their relative contributions to the Cepheid flux measured on ground-based images insignificant in most cases. This is good news for ground-based Cepheid distance work on relatively distant galaxies.

Since the LMC Cepheids are currently providing the fiducial PL relations for the distance determination of other galaxies, owing to the very large number of Cepheids discovered by the OGLE-II and other microlensing projects, it is extremely important to establish the Cepheid PL relations (in different bands) in the LMC with the highest possible accuracy. Since the existing microlensing surveys have not found many long-period Cepheids in the LMC, due to long integration times which overexposed any Cepheids longward of periods of ~ 30 days, we are currently undertaking a "shallow" Cepheid survey in the LMC with the Polish 1.3-m telescope on Las Campanas which is expected to discover a large number of new bright, long-period Cepheids close to the bar. These data, which cover most of the spatial extent of the LMC and which will become available in 2007, will also decide the nagging question of whether the LMC Cepheid PL relation shows a break near 10 days, as claimed by Sandage et al. (2004). Such a departure from a uniform slope over the whole period range, if real, would evidently constitute a serious problem in the use of the Cepheid PL relation for distance work. If the break at 10 days turns out to be real, new fiducial LMC PL relations must be established in the period range longwards of 10 days, which is the relevant range for the measurement of the distances of galaxies beyond about 1 Mpc. Our current "LMC shallow Cepheid survey" is expected to provide a significant improvement of the calibration of the LMC Cepheid PL relation in V and I, and provide a definitive answer about the reality of a period break in the relation.

Cepheid work in the near-infrared

There are at least three substantial advantages when Cepheid distance work is carried out in near-infrared bands. The first obvious advantage is the strong reduction of the effect of dust absorption. A second advantage is that Cepheid light curves in the near-infrared, and particularly in the *K*-band, are more symmetrical than their optical light curves, and have smaller amplitudes. This makes it possible to measure a Cepheid's mean *K*-band brightness with a very good precision from just one random phase photometric observation, if the star's optical light curve and period is known (Soszynski et al. 2005). *K*-band PL relations can therefore be determined very economically if the Cepheids of a galaxy have been previously found and characterised in the optical spectral range.

In addition to these important advantages, theoretical studies suggest an even smaller dependence of the PL relation on metallicity in the near-infrared, as compared to optical wavelengths.

For these reasons, we have been undertaking near-infrared follow-up imaging for selected subsamples of long-period Cepheids in most of the target galaxies of our project. We have been obtaining these images using VLT/ISAAC, and the NTT with the SOFI instrument. Superb results are being obtained from these very high-quality data, as recently demonstrated in the case of NGC 300. Figure 5 shows the PL relations in the *J*- and *K*- bands obtained from our VLT images for this galaxy, which have led to a very accurate determination of the distance to NGC 300 by combining the near-infared and optical data for this galaxy (Gieren et al. 2005b; see also a recent August 1, 2005 ESO Press Release). The work on NGC 300 has shown how essential infrared images are to achieve an accurate determination of the reddening of a galaxy, including the contribution coming from dust absorption inside the galaxy. Only in this way can it be hoped to achieve the final goal of the Araucaria Project, which is to measure the distances to nearby galaxies with a precision of at least 5 per cent, or better.

Blue supergiants

The spectroscopy of blue supergiants, the brightest young stars visible in galaxies, and among the most massive, is an integral part of the Araucaria Project. The goal of our detailed study of these stars is twofold: to measure chemical abundances of heavy elements and to develop and apply a new distance determination technique based on a small set of fundamental stellar parameters.

Gathering information on the metal content of galaxies is essential to obtain accurate distances, since the techniques used, such as the Cepheid PL relation, could significantly depend on metallicity. The chemical abundances in spiral and irregular galaxies are commonly obtained from the spectroscopic analysis of giant H II regions, resulting from the photoionisation of gas clouds by hot stars. There are, however, considerable uncertainties on the gas-phase abundance scale at high metallicity (around the solar value and above), as encountered in the central regions of spiral galaxies (Bresolin et al. 2005b). Stellar abundance studies allow us to circumvent this difficulty, although the chemical analysis in young massive stars is a complex task, due to strong departures from conditions of local thermodynamic equilibrium and to the effects of stellar winds on the atmospheric structure. It is important to note that both the blue supergiants and the H II regions are young (< 10–20 million years) objects, and therefore the galactic chemical abundances derived from them are relevant for the study of young stellar distance indicators, such as Cepheids.

The analysis of the chemical composition of blue supergiants complements the study of H II regions, which is limited mostly to the abundances of oxygen, nitrogen and sulphur, by providing information not only for these elements, but also for additional species, such as magnesium, iron and silicon. Model spectra, calculated accounting for the presence of millions of atomic transitions, are compared to the observed supergiant spectra to measure the abundances of these metals. An example of this procedure is shown in Figure 6, taken from our chemical analysis of early B-type supergiant stars in NGC 300 (Urbaneja et al. 2005). By combining our good-quality data with modern stellar-atmosphere analysis techniques for massive stars we have been able to compare for the first time in a galaxy located outside the Local Group the chemical abundance gradient in its disc obtained independently from the stellar analysis, and from the ionised gas (Figure 7).

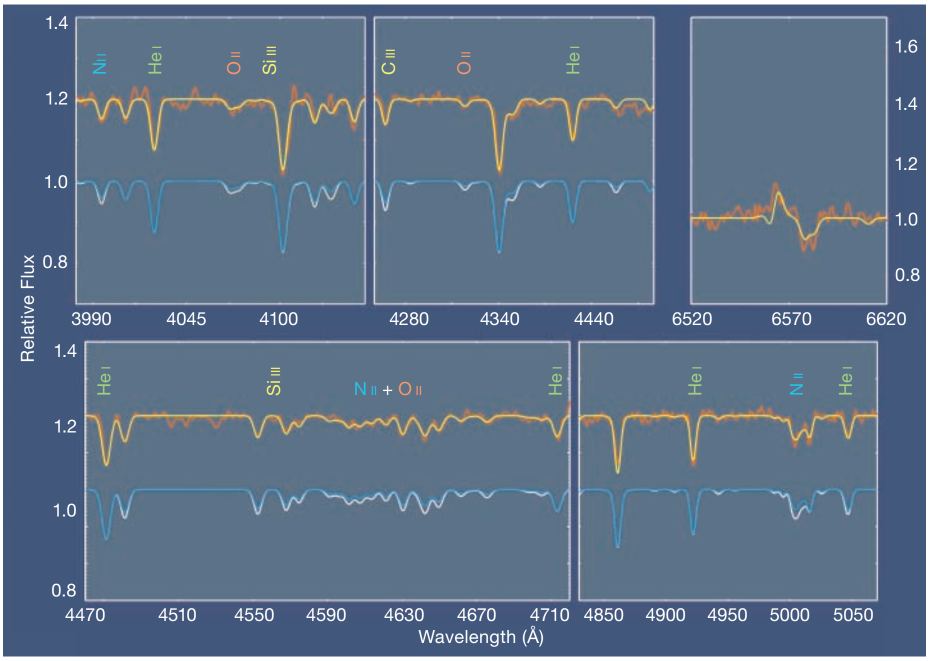


Figure 6: The technique used to measure the abundance of metals of blue supergiants is shown here. With the stellar gravity fixed by fits of model spectra to the high-order Balmer lines and the effective temperature determined from line diagnostics, the abundances of different elements are varied in the models until the best fit (in yellow) to the observed spectrum (orange line) is obtained. The sensitivity to the abundance is indicated in the lower part of the panels, where models differing by ± 0.2 dex relative to the best-fitting model are compared. The effects of strong stellar winds in this B3 supergiant in NGC 300 are visible in the Hα line, which is in emission (upper right).

The NGC 300 observations were carried out utilising the multi-object spectroscopic capabilities of FORS at the VLT, yielding intermediate-resolution spectra of several dozens of stars in this galaxy (Bresolin et al. 2002). This observing strategy, repeated for all the galaxies included in the Araucaria Project, has allowed us to collect several hundred spectra of blue supergiant candidates (the case of NGC 247 in Sculptor is shown in Figure 8). This represents an unprecedented sample of extragalactic massive star spectra, of

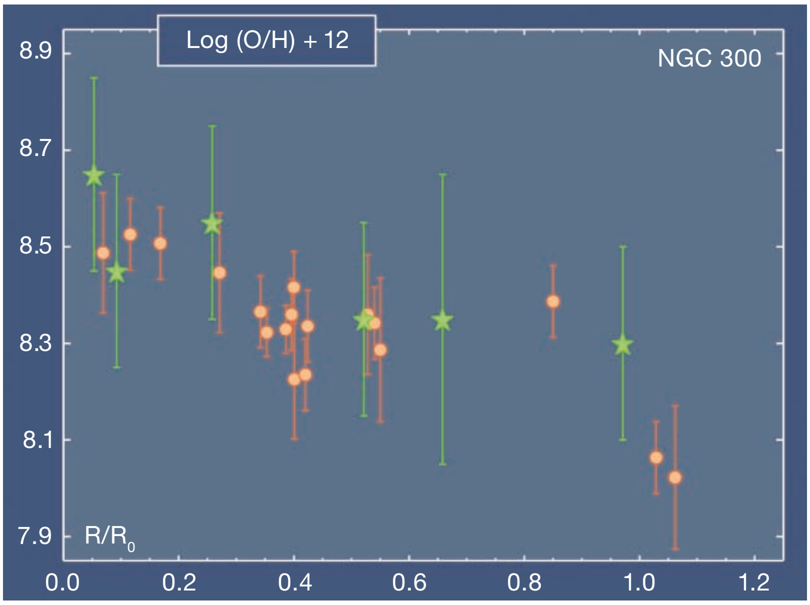
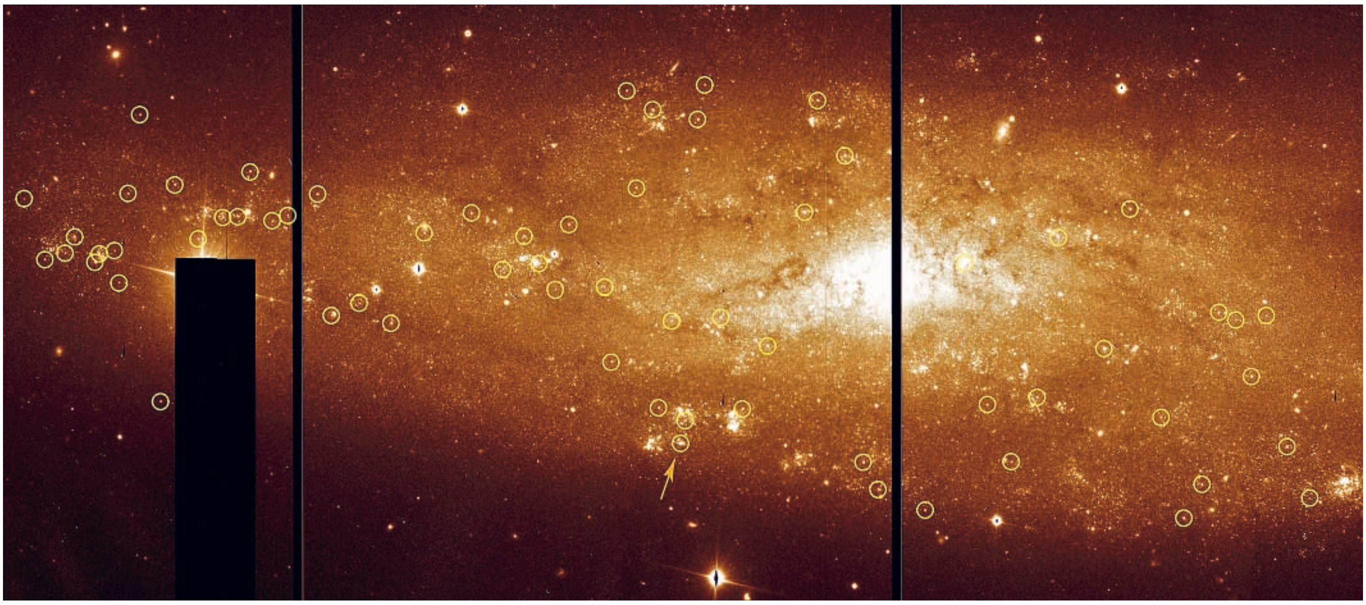


Figure 7 (left): A comparison of the radial oxygen abundance gradient in NGC 300 obtained from the B supergiants (green star symbols) and the H II regions (orange disks). The oxygen abundance is in the 12 + log(O/H) scale, commonly adopted in nebular work (the solar value is ~ 8.7 on this scale), while the horizontal coordinate is the deprojected galactocentric distance in units of the isophotal radius. The nebular abundances have been obtained from the emission line fluxes available in the literature and adopting the Pettini & Pagel (2004) calibration of the R_{23} abundance indicator.

Figure 8 (below): Over 60 blue supergiant candidates have been observed spectroscopically in the Sculptor Group galaxy NGC 247, as indicated here on a mosaic derived from FORS images. The arrow points to the emission line star whose spectrum is shown in Figure 9. Candidates for the FORS/MXU spectroscopic follow-up were selected from colours and magnitudes measured from 2.2-m telescope WFI images.



great value for the immediate needs of the project (abundances and luminosities), and for future research on normal B- and A-type supergiants, as well as on more exotic, rare objects, like the extremely luminous emission-line star we discovered in NGC 247 (Figure 9). A dedicated analysis technique is being developed by our group in order to cope with the large amount of stars for which we are deriving the basic parameters (gravities, temperatures and metallicities).

Thanks to their extreme luminosity in the optical range (with absolute magnitudes in V between –7 and –10), blue supergiants are among the brightest stellar objects observed in galaxies, second only to supernovae. The investigation of their usefulness as extragalactic distance indicators, therefore, is a natural component of the Araucaria Project. A simple but powerful technique was developed by Kudritzki et al. (2003), who found that the *flux-weighted gravity* g/T_{eff}^4 (the gravity g and the effective temperature T_{eff} are both determined from the spectra) is strongly correlated with the intrinsic luminosity of blue supergiants, and appears to be quite insensitive to metallicity variations.

The *Flux-weighted Gravity-Luminosity Relationship* (FGLR) determined from our analysis of blue supergiants (spectral types from early-B to mid-A) in galaxies of the Local Group and in NGC 300 is shown in Figure 10. The calibration we have obtained can be used to measure distances to galaxies where spectra and apparent magnitudes of blue supergiants are available. This independent spectroscopic method, despite the complexities involved in the data analysis, provides simultaneously the luminosities, as well as the chemical abundances of the target stars. In this respect, the FGLR has an

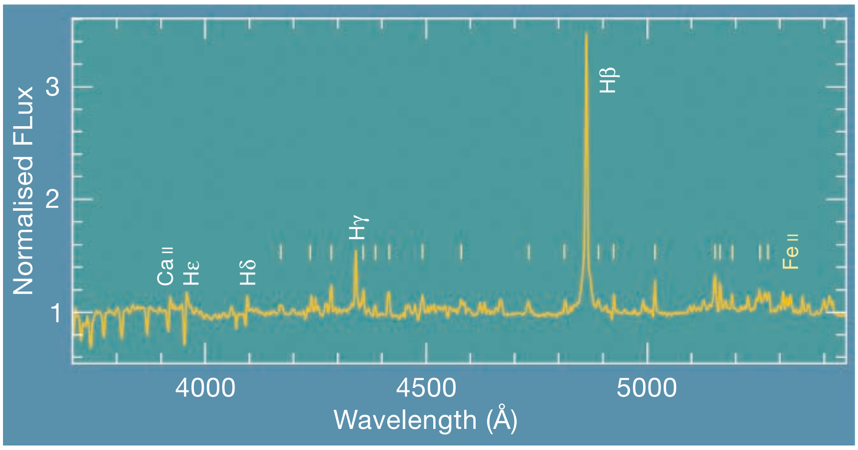


Figure 9: The FORS2 spectrum of an extremely luminous (M_V ~ −9.3) blue supergiant star in NGC 247. A strong stellar wind is responsible for the emission lines visible throughout the spectrum (a nebular component is also present for the Balmer lines), which is reminiscent of the spectra of Luminous Blue Variables. Most of these features are due to Fe II, as identified by the vertical bars.

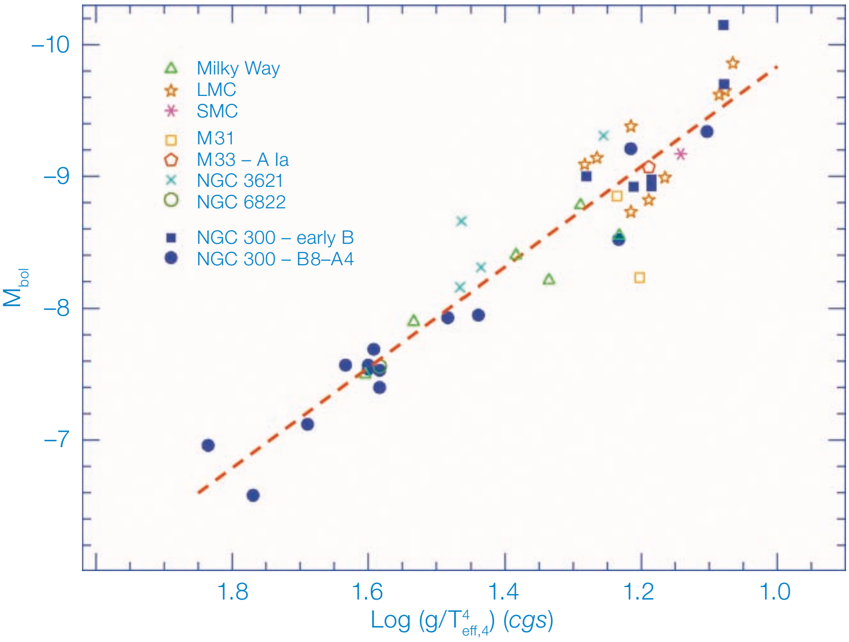


Figure 10: The Flux-weighted Gravity-Luminosity relationship is plotted here for blue supergiants analysed in the Local Group and in NGC 300. The legend shows the meaning of the different symbols used. The data are taken from Kudritzki et al. (2003), except for the early B-type supergiants in NGC 300, which are taken from Urbaneja et al. (2005).

advantage over the photometric methods of distance determination (Cepheids, TRGB, etc.), in that it allows us to account directly for the effects that metallicity has on the distances derived.

Acknowledgements

We thank the ESO Observing Programmes Committee for the generous allocation of observing time to our project. It is a pleasure to thank ESO staff on Paranal and La Silla for their expert collaboration in obtaining those observations which were scheduled in service mode. Wolfgang Gieren, Grzegorz Pietrzynski, and Dante Minniti acknowledge support from the Chilean FONDAP Center for Astrophysics for this research. Last not least, we want to thank the different members of the OGLE Project for helping out with the observations for this programme at the Polish telescope on Las Campanas.

References

Bresolin, F., Gieren, W., Kudritzki, R. P. et al. 2002, ApJ 567, 277
Bresolin, F., Pietrzynski, G., Gieren, W., Kudritzki, R. P. 2005a, ApJ, in press
Bresolin, F., Schaerer, D., González-Delgado, R. M., Stasinska, G. 2005b, A&A, in press
Freedman, W. L. et al. 2001, ApJ 553, 47
Gieren, W., Pietrzynski, G., Walker, A. et al. 2004, AJ 128, 1167
Gieren, W., Storm, J., Barnes III, T.G. et al. 2005a, ApJ 627, 224
Gieren, W., Pietrzynski, G., Soszynski, I. et al. 2005b, ApJ 628, 695
Kudritzki, R. P., Bresolin, F., Przybilla, N. 2003, ApJ 582, L83
Persson, S. E., Madore, B. F., Krzeminski, W. et al. 2004, AJ 128, 2239
Pettini, M., Pagel, B. E. J. 2004, MNRAS 348, L59
Pietrzynski, G., Gieren, W., Fouqué, P., Pont, F. 2002, AJ 123, 789
Pietrzynski, G., Gieren, W., Udalski, A. et al. 2004, AJ 128, 2815
Sandage, A., Tammann, G. A., Reindl, B. 2004, A&A 424, 43
Soszynski, I., Gieren, W., Pietrzynski, G. 2005, PASP 117, 823
Udalski, A. 2000, AcA 50, 279
Urbaneja, M. A., Herrero, A., Bresolin, F. et al. 2005, ApJ 622, 862