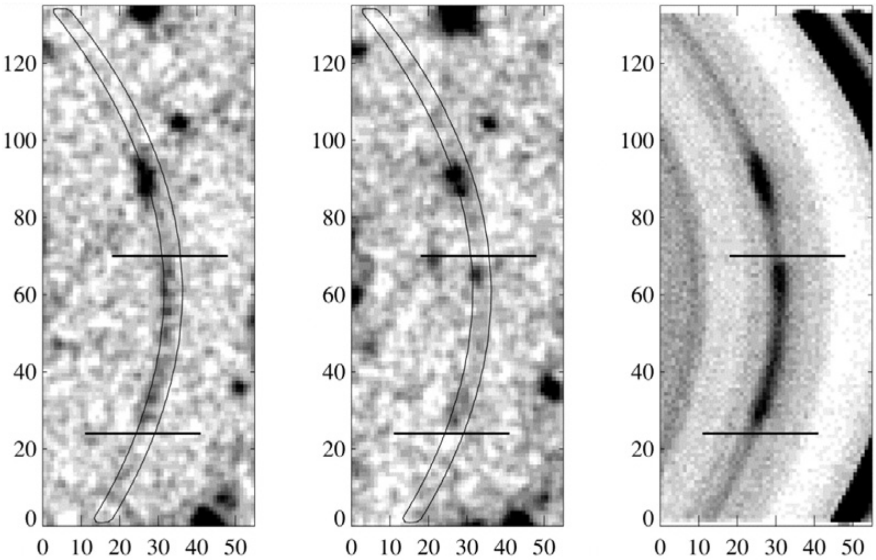

Figure 6: Arc C in R band (left), I band (middle), and in Ly emission (right). The spectral image has not been sky subtracted. The position of the slit as reconstructed after the FORS observations, is also indicated in the broadband images.(Adapted from Gladders et al. 2002)

are fully characterized by their corresponding halo dark matter mass. If so, how can observations be used to measure the *"bias"* ? Theoretically, there is a strong relation between the dark matter halo mass and the number of members with similar luminosities in clusters, cluster number richness, *m*. In the observational plane, the measured quantities are N(*z,m*) and the two-point correlation function, ξ(r,m).

No clustering studies of small galaxy groups with $m > 3$ have been carried out, basically because of small survey area, bad number statistics and lack of deep homogeneous data. To find groups at different redshifts, deep wide field imaging is needed. In this project, SDSS and RCS provide the low and high-*z* groups, to $z < 0.7$ respectively. A number of groups have been detected on the RCS data. In order to measure the spatial clustering properties, inversion of 2-dimensional data is required. Currently, redshifts of group members selected from SDSS and RCS are being measured.

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Long Period Variables in the Giant Elliptical Galaxy NGC 5128: the Mira P–L Relation at 4 Mpc

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In a stellar population older than a few hundred Myr, the near-infrared light is dominated by red giants. Among these, the stars lying on the red giant branch (RGB) are the brightest among the metal poor stars older than 1–2 Gyr. In intermediate-age populations (~ 1–5 Gyr old) numerous bright asymptotic giant branch (AGB) stars are located above the tip of the RGB. However, also among old populations like Galactic globular clusters with [Fe/H] ≥ –1.0 and in the Galactic bulge, bright stars have been detected above the tip of the RGB implying the presence of bright AGB stars in metal-rich and old populations. All of the bright giants above the RGB tip in globular clusters seem to be long period variables (LPVs; Frogel & Elias 1988). Old populations of lower metallicity are known not to have AGB stars brighter than the RGB tip.

Long period variables are thermally pulsing asymptotic giant branch (TP-AGB) stars with main sequence masses between 1 and 6 $M_{\odot}$. They have variability with periods of 80 days or longer, and often the longest period variables show variable or multiple periods. Two main classes of LPVs are Mira variables (Miras) and semi-regular variables (SRs). SRs usually have smaller amplitudes as well as shorter and more irregular or even multiple periods. They are sometimes divided into subclasses (SRa, SRb) depending on the regularity and multiplicity of their periods and shape of their light curves. The separation between Miras and SRs is not always very clear. The classical definition requires that Miras have *V*-band amplitudes larger than 2.5 mag and regular periods in the range of 80–1000 days. Mean *K*-band amplitudes of Miras are typically 0.6 mag. SRs show more irregular variability, as their name indicates, and have smaller amplitudes.

So far, LPVs have been studied in the Milky Way, Magellanic Clouds and a few other Local Group galaxies. However, the Local Group lacks the important class of giant elliptical galaxies. At the distance of about 4 Mpc (Harris et al. 1999), NGC 5128 (Centaurus A) is the closest giant elliptical galaxy, the closest active galactic nucleus (AGN), one of the largest and closest radio sources and a classical example of a recent merger. It is the dominant galaxy of the nearby Centaurus Group of galaxies. Rejkuba et al. (2001) presented optical-near-IR colour-magnitude diagrams (CMDs) of two fields in the halo of this giant elliptical galaxy (Figure 1). These CMDs show broad giant branches indicating a large spread in metallicity. The RGB tip is detected at $K \sim 21.3$.

A large number of sources are observed brighter than the tip of the RGB. These can belong to one of the three categories: *(i)* intermediate-age AGB stars with abundances similar to those found in Magellanic Clouds, *(ii)* old and metal-rich AGB stars similar to those found in the Galactic Bulge and metal-rich globular clusters, or *(iii)* blends of two or more old first ascent giant branch stars. While Rejkuba et al. (2001) have shown with simulations that only a small part of these sources can be ascribed to blends, a definite proof that these bright red giants belong to the AGB population in NGC 5128 is through the detection of variability of these sources. Furthermore, the near-IR properties of long period AGB variable stars can be used to investigate the presence or absence of an intermediate-age component in the stellar populations of this giant elliptical galaxy. This has important consequences for the formation and evolution of giant elliptical galaxies.

Using the multi-epoch *K*-band photometry we investigated the nature of bright giants observed above the tip of the RGB (Figure 1) in two halo fields in NGC 5128. Field 1 is located in the north-eastern halo of the galaxy and it coincides with the prominent diffuse stellar shell, presumably a remnant from a recent merger. Field 2 is in the southern halo of the galaxy. The data were taken in the *K*-band over three years with ISAAC at the VLT. As a result of this long term program, which required repetitive observations of the same halo fields, we have discovered more than 1000 long period and large amplitude red variable stars confirming the presence of an AGB population in this giant elliptical galaxy halo.

ISAAC photometry

We obtained a total of 20 epochs of *K*-band photometry in Field 1 and 24 epochs in Field 2 in the time interval between April 1999 and July 2002. The data were obtained in service mode with ISAAC at the VLT, except one Field 2 epoch, which was secured on an observing run in February 2000 with SOFI at the NTT under exceptional seeing conditions. The exposure times for different epochs varied due to changes in seeing and sky conditions, but on average one hour of observation was taken per epoch for each field. The total exposure times amount to 19.7 and 21.1 hours for Fields 1 and 2, respectively. These are the deepest near-IR images taken so far in the halo of an elliptical galaxy.

Data reduction included dark subtraction, flat-fielding and sky subtraction. For each epoch, a single image was obtained combining individual frames obtained with short (60 sec) exposures that were dithered in an automatic pattern in order to allow the sky subtraction in this stellar field. Each of these 60-sec exposures was already an average of six 10-sec exposures. It is necessary to average a large number of such very short exposures due to high background emission of the sky in near-IR wavelengths. The PSF fitting photometry was done for each single-epoch image individually. The final photometric catalogue contains 13,111 stars in Field 1 and 16,435 stars in Field 2, which have been detected on at least 3 *K*-band frames as well as in *J* and *H*-band images.

A combined colour image for Field 2 of *J, H* and the best-seeing epoch in *K*-band is shown in Figure 2. Figure 3 shows a small portion of this field, along with five *K*-band epochs in which several large amplitude stars can be seen. Most of these correspond to red sources on the colour image.

Long period variable stars

Variable stars were identified using a procedure similar to the one described by Stetson (1996). First, we selected all the stars with mean photometric errors given by ALLFRAME smaller than 0.2 mag. We then required each star to be detected on more than 5 frames and constructed variability indices which measure time-dependent correlation of magnitude residuals. In other words, given a mean magnitude and taking into account photometric errors, variability indices show how much a stellar brightness varies between different observations. With these indices, we found that 601 stars in Field 1 and 903 stars in Field 2 have periodic variations. Of these, 536 and 878 had at least 10 measurements with individual errors smaller than 0.5 mag, and for these we constructed light curves.

A Fourier analysis of the *K*-band light curves was used to search for the periodic signal in the data. The period obtained from the frequency with largest power corresponds to the most probable sinusoidal component. It was further improved with a non-linear least-square fitting of the sine-wave. From this, the best-fitting period *(P)*, amplitude, mean magnitude and phase were obtained. In optical passbands Miras often have asymmetric light curves, usually steeply rising to the maximum and with a shallower decline. In the near-IR the variations are more regular and nearly sinusoidal. Hence a sine-wave is a good approximation to most of the LPVs.

For 99 variable stars in Field 1 and 169 in Field 2, no acceptable periods could be obtained because of the non-sinusoidal variations, large errors combined with small amplitudes, multiple periods, presence of irregular period or cycle-to-cycle variations typical for Miras and semi-regular variables, or absence of period (e.g. microlensing, background AGN or SN). In Figure 4, we show a sample of good light curves folded with the periods that are indicated in each panel. Note that each point is plotted twice to emphasize the variability.

The mean amplitude of all the variables for which we could measure periods is 0.7 mag, and the majority have periods in the range of 150 to 500 days. With 24 or fewer measurements per star obtained over an interval of 1,197 days, and with observations distributed in 3–6 month intervals interspaced by ~6 months gaps, there may be some period aliasing. However, most of the determined light curves are of good quality (see Figure 4). For some of the variables the best fitting periods were longer than 600 days and these need to be confirmed with observations over a longer time baseline. The amplitudes and periods of the LPVs are characteristic of Mira variables and are similar to those found in the LMC, SMC and Galactic Bulge. These are the most distant Miras for which periods have been measured and the first in an elliptical galaxy.

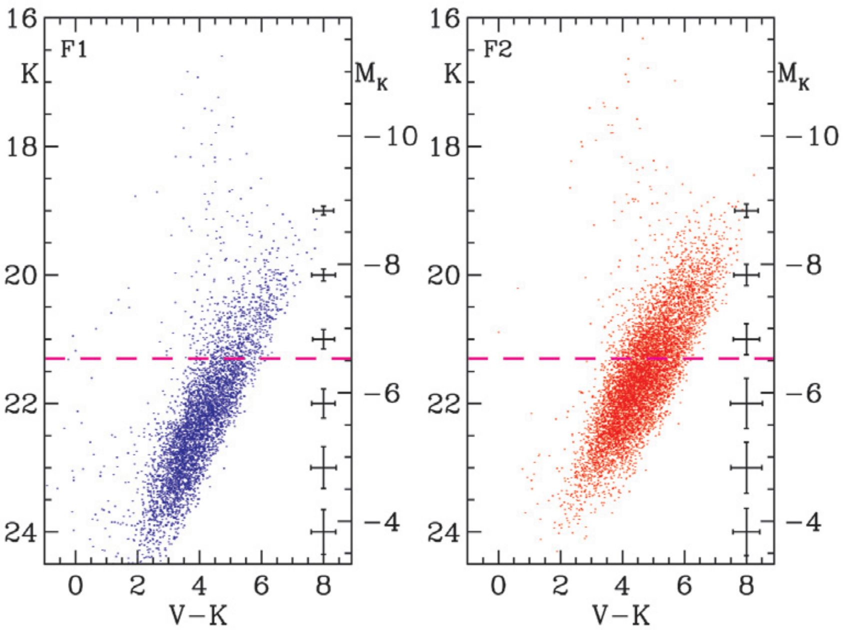


Figure 1: Optical-infrared CMD for 5630 stars in the NGC 5128 shell field (F1; left) and 9001 stars in the NGC 5128 halo field (F2; right), based on ISAAC+FORS1 images of a region covering 2′5 × 2′5 (Rejkuba et al. 2001). A large number of stars brighter than the tip of the RGB, K ≤ 21.3 (magenta dashed line), are LPVs.

The NGC 5128 distance with the Mira P-L relation

A well-defined period-luminosity (P-L) relation has been found for Miras in the Large Magellanic Cloud (Glass & Lloyd Evans 1981, Wood 1999), the Small Magellanic Cloud (Cioni et al. 2003), the Galactic Bulge (Glass et al. 1995), the solar neighbourhood (van Leeuwen et al. 1997) and in Galactic globular clusters (Feast et al. 2002).

The relation holds for both M_{bol} and M_K. Since Miras are very luminous, their tight P-L relation makes them interesting for distance determination to other galaxies.

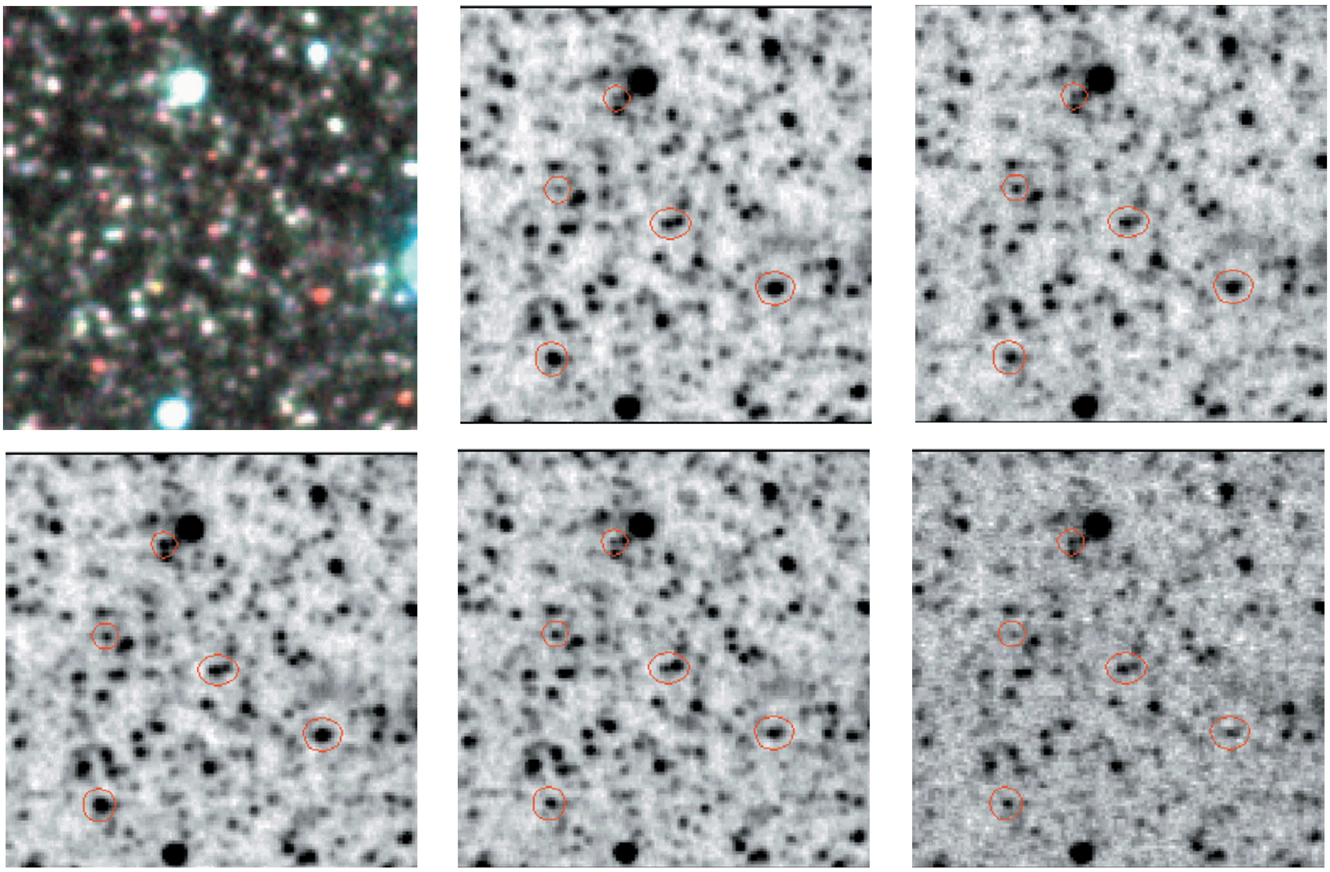
Our data are not sufficient to discriminate Mira from SR variables on the basis of the regularity of their light curves. Hence, to select the most probable Miras we made a selection on period ($2 < \log P(d) < 2.6$) and on amplitude (0.5 mag $< \Delta K < 1.5$ mag). The mean magnitudes derived from the non-linear sine-wave fit were corrected for extinction by subtracting $A_K = 0.039$, corresponding to $E(B–V) = 0.11$. The period-luminosity diagram is displayed in Figure 5. Field 1 variables are plotted with blue and Field 2 variables with red symbols. Variables with better determined periods based on the significance parameter from Fourier fitting algorithm are plotted with larger symbols.

Most of these Mira variables are located where expected, along a well populated sequence in the P-L diagram. This is the first time a Mira P-L relation has been observed in a galaxy outside the Local Group.

Calibration of the P-L relation relies on the LMC P-L relation for Miras. Feast et al. (1989) fit to the LMC Mira P-L relation is: $M_K = -3.47 \log P + \beta$. The zero

▲ *Figure 2: A combined color image for Field 2. The* J*-band is coded in blue, the* H*-band is green and the* K*-band image is red. This field is located roughly 9′ (corresponding to 10.5 kpc at the distance of 4 Mpc) south of the centre of the galaxy. The total exposure time for each band is 1 hour and the field of view is 2′.0 × 2′.07. North is up and east to the right. Note the large number of red sources – most of these are long period variable stars.*

▼*Figure 3: Zoom of a 131 × 131 pix (19″4 × 19″4) region showing variable stars in Field 2. Most of the red stars are variable. There is a pair of stars in the centre of this field that varies in counter-phase with similar periods.*



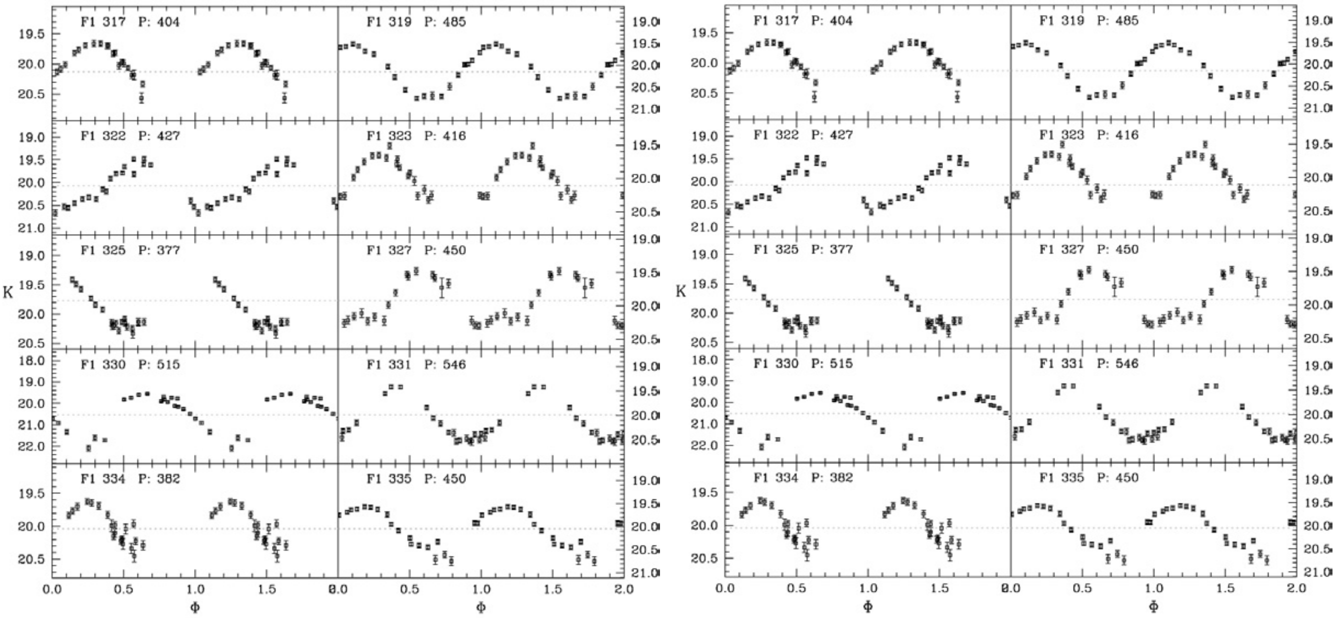


Figure 4: A sample of phased K*-band light curves from both fields. Periods (P) are indicated in each panel. Each point is plotted twice to emphasize the variability.*

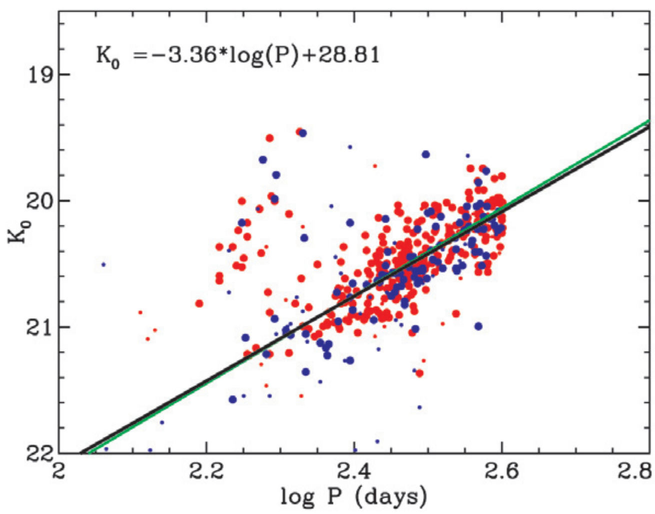


Figure 5: Period-Luminosity diagram in NGC 5128 for long period (2 < log P*(d) < 2.6) and large amplitude (0.5 < Δ*K *< 1.5 mag) variables. Large symbols are used for Miras with more significant periods. Field 1 variables are blue and Field 2 are red. The black line is our best fit to the Mira sequence. The green line is the best fit to the Mira sequence adopting the slope of –3.47 (Feast et al. 1989).*

point β = 0.88 ± 0.10 has been recently derived using *Hipparcos* parallaxes for Miras in the solar neighbourhood and in well-studied Galactic globular clusters (Feast et al. 2002). With such a calibration, the Large Magellanic Cloud distance modulus is 18.60 ± 0.10.

A least-squares fit to the Mira sequence in NGC 5128 is:

$K_0 = -3.36\ (\pm 0.13) \log P + 28.81\ (\pm 0.32)$.

This fit is overplotted as a solid black line in Figure 5. The 1σ scatter around the fit is 0.19. Fixing the slope to be –3.47, the best fitting zero point is 29.09 ± 0.32 (solid green line in Figure 5), with the same RMS of the fit.

Finally, the derived distance modulus to NGC 5128 is 28.21 ± 0.32, assuming a LMC distance modulus of 18.60. If 18.5 is preferred (e.g. Alves et al. 2002), the distance modulus to NGC 5128 would be 28.11 ± 0.32, in good agreement with that derived from the RGB tip (Harris et al. 1999).

Conclusions

ISAAC multi-epoch *K*-band photometry of two fields in the halo of NGC 5128 was used to detect variable stars. We derived periods for most of these variables via Fourier analysis of the *K*-band light curves and sine-wave fitting. Their magnitudes indicate that they are in the AGB phase and their periods and amplitudes are consistent with being LPVs.

The long-period (400 ≥ *P* ≥ 100 d) large-amplitude (0.5 < *ΔK* < 1.5 mag) Mira variables were used to determine the distance of NGC 5128 from a P-L relation. Adopting a LMC distance modulus of 18.50, we derive the distance modulus of 28.1 ± 0.3, corresponding to D = 4.2 ± 0.6 Mpc.

In closing, we would like to note that such programs that require numerous (>10) and relatively short (~ 1.5 h per Field) observations benefit greatly from the availability of service mode observations. All the images were taken in excellent seeing conditions, ranging from 0″.35 – 0″.65, enabling us to detect variable stars in a giant elliptical galaxy for the first time and construct the first Mira period-luminosity diagram outside the Local Group. The catalogue with light curve parameters and near-IR photometry of all the variable stars is available through Astronomy & Astrophysics (Rejkuba et al. 2003).

Acknowledgements

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