Red Giants in the Halo of the S0 Galaxy NGC 3115:
A Distance and a Bimodal Metallicity Distribution

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1 Based on observations obtained as part of the Medium Deep Survey.
Abstract

Using the Hubble Space Telescope, we resolve the red giant branch in the halo of the S0 galaxy NGC 3115. We measure magnitudes and $(V-I)$ colours for stars down to 1.5 magnitudes below the tip of the red giant branch. From the brightest stars we estimate a distance modulus $(m-M)_0 = 30.21 \pm 0.30$, corresponding to a distance of $11.0 \pm 1.5$ Mpc. This is in excellent agreement with the value $(m-M)_0 = 30.17 \pm 0.13$ determined from the planetary nebula luminosity function. Our results rule out the shorter distance modulus $(m-M)_0 = 29.65$ determined from surface brightness fluctuations. A histogram of $(V-I)$ colours shows a clear bimodality, indicating the presence of two distinct halo populations of roughly equal size. One has $[\text{Fe/H}] \sim -0.7$ and one has $[\text{Fe/H}] \sim -1.3$. This is the most distant galaxy in which a Population II halo has been resolved, and it is the first time a colour bimodality has been observed among the halo stars of any early-type galaxy.

Key words: Galaxies: Abundances : Stellar Content : Distances : Individual: NGC 3115

1. Introduction

With the advent of the Hubble Space Telescope (HST), the brightest giants in galaxies as far away as the Virgo cluster are being resolved. Since the magnitude of the tip of a Population II red giant branch (the TRGB) is relatively insensitive to metallicity or age, it therefore provides a reliable distance indicator (cf. Lee, Freedman & Madore 1993). This method has been applied to a variety of galaxy types within $\sim 1.5$ Mpc using ground based observations, (Lee et al. 1993; Sakai,
Madore, & Freedman 1996), and more recently, using HST, to NGC 5128 at 3.6 Mpc (Soria et al. 1996). A good discussion of the method for determining the magnitude of the TRGB, and the uncertainties introduced by photometric errors, crowding, population size, and background contamination is given by Madore & Freedman (1995).

As the accuracy of the photometry of such distant stars improves, we should obtain, in addition to better distance estimates, a more thorough understanding of the nature of stellar populations in the halos of early type galaxies, of which we have no local examples. For example, the colour of the red giant branch should indicate the range of metallicities present. Soria et al. find that the colour of the red giant branch in the halo of NGC 5128 indicates a broad range of metallicities, with a mean value \([\text{Fe/H}] > -0.9\). Until now, such metallicity estimates have relied only on the interpretation of integrated light.

In this paper we present photometry for ~4700 halo stars in NGC 3115, an edge-on S0 field galaxy thought to be an extinct quasar with a ~10^9 M_\odot black hole at its centre (cf. Kormendy et al. 1996). We use the magnitude of the TRGB to estimate the distance, and the distribution of colours to explore the chemical compostion of the halo. The data, obtained with HST as part of the Medium Deep Survey (cf. Griffiths et al. 1994), are described in Section 2. Determination of the distance to NGC 3115 is discussed in Section 3, and the metallicity of the sample is analysed in Section 4. The results are summarized in Section 5.

2. The Data, Sample Selection, and Photometry
This study is based on a field 8.5 arcmin (∼ 30 kpc) east of the centre of NGC 3115, and 5 arcmin (∼ 18 kpc) away from the major axis of the (edge-on) disk. Exposures in two filters (F814W = I\textsubscript{814} and F606W = V\textsubscript{606}) were acquired on 1994 December 27. A total of 11 exposures were obtained in I\textsubscript{814}, with a total exposure time of 6.4 hours, and 10 in V\textsubscript{606}, with total time 4.6 hours. The images in each passband were co-added with a median filter. Only the three Wide Field Camera chips were considered. They have image scale 0.10 arcsec pixel\(^{-1}\), and total area, excluding borders, of 4.56 arcmin\(^2\). The FWHM is ∼ 1.5 pixels. In order to ensure consistent selection criteria, we did not use the PC chip; with area only 0.36 arcmin\(^2\) it would increase our sample size by less than 10%.

We used the DAOPHOT task DAOFIND to detect automatically all stellar objects in the deeper I\textsubscript{814} image. We set the detection threshold to 3\(\sigma\). In practice, DAOFIND detects, in addition to stars, a large fraction of the background galaxies in the field, as well as spurious sources along diffraction spikes and structure in the point-spread function (PSF) surrounding bright (foreground) stars.

To discard non-stellar detections, we constructed a PSF from two bright, unsaturated foreground stars in chip 2, and fit this to all objects detected in the I\textsubscript{814} image, using a fitting radius of 10 pixels. We then used the output fitting parameters from ALLSTAR to isolate a sample of stars, and eliminate most background galaxies and spurious detections. Figures 1a and b show the “sharpness” and the Poisson error in the magnitude plotted against I\textsubscript{814} for all detections. The sharpness parameter measures the ratio of heights of the best fitting delta function and Gaussian function. Also shown are artificial stars created and measured using the same procedure as for the real objects.
Figure 1a shows a concentration of objects around sharpness=0, which are consistent with being stars. A secondary sequence is also visible around sharpness \( \sim 0.1 \). In Figure 1b there is a concentration of points with larger errors at a given magnitude than expected on the basis of simulations. Inspection of these outlying points reveals that they are either spurious detections or background galaxies. (A very bright foreground star just out of the field is responsible for pronounced diffraction spikes running across two of the chips.) Our selection criterion for stellar objects is illustrated with the solid lines in Figs. 1a and b. Our final photometry list contains \( \sim 4700 \) candidate giant branch stars.

It is our experience that with stellar photometry on poorly sampled images, better results (as judged by the narrowness of the stellar sequence in a colour-magnitude diagram (CMD)) are often achieved with aperture photometry rather than with PSF fitting. Experiments showed that this is indeed the case here. Our final magnitudes were therefore measured with an aperture of radius 2 pixels. We applied the following corrections: an absorption \( A_I = 0.05 \) (Ciardullo, Jacoby & Tonry 1993); an adjustment for geometric distortion; an aperture correction to transform from 2 pixel to total (r=10 pixel) magnitudes. Finally, we converted the instrumental ‘flight system’ magnitudes to the Johnson-Cousins system. All the corrections and transformations were applied following Holtzman et al. (1995a,b).

Figure 2 shows a CMD for the \( \sim 4700 \) objects. There is a clear cutoff at \( I_0 \sim 26 \), and only a few objects brighter than this. The majority of these are very blue, and are probably compact background galaxies (cf. Elson, Santiago & Gilmore 1996). A few may be blends of two individual giants, and a few with \( (V-I)_0 \gtrsim 2 \) may be AGB stars.
3. Determining the Distance to NGC 3115

As long as the stars in our field are metal poor ([Fe/H] ≲ −0.7), we may assume an absolute magnitude of \( M_I = 4.00 \pm 0.10 \) for the TRGB, regardless of the precise metallicity of the population (Lee et al. 1993). Since our field lies well away from the NGC 3115 disk, it should be dominated by halo stars. Colour gradients measured along the minor axis of NGC 3115 show that the \((B - V)\) colour becomes bluer with radius, and by \( r \sim 5 \text{ kpc} \), \((B - V) \sim 0.8\) (Strom et al. 1976). This is only 0.1 mag redder than the mean for Galactic globular clusters, which have mean metallicity well below [Fe/H] = −0.7. The assumption that [Fe/H] ≲ −0.7 in our halo field is further supported by surface photometry in \( B \) and \( R \) by Surma, Seifert & Bender (1990), and by our own results in Section 4 below.

Our primary task is therefore to determine the precise magnitude of the TRGB, and to estimate its uncertainty. We adopted as the TRGB the brightest magnitude at which the giant branch luminosity function steepens dramatically. To quantify this, we calculated a derivative across bins of 0.1 to 0.4 mag for luminosity functions drawn from different samples. We also used a Sobel filter as described in Madore & Freedman (1995), with software kindly provided by S. Sakai. All the methods gave values converging on \( I_0 = 26.15 \), as we now discuss.

Figures 3a-c show the value of the derivative of the luminosity function plotted against \( I_0 \) for the following samples:

(a) The full sample with steps 0.1 – 0.4 mag.

(b) Subsamples from chips 2, 3 and 4 with step 0.2 mag.
(c) The sample of objects redwards of the dashed line in Fig. 2, with steps 0.1, 0.2 and 0.3 mag.

Figure 3d shows the output from a Sobel filter, again for the three individual chips, for the red sample, and for the full sample.

Figures 3a-c show two, or in some cases three prominent peaks. In the cases where two peaks are present, their values, averaging over all cases, are $I_0 = 26.14 \pm 0.04$ and $I_0 = 26.41 \pm 0.06$. In a few cases there is a brighter, smaller, peak with $I_0 = 25.92 \pm 0.02$. The first main steepening in the luminosity function thus occurs at $I_0 = 26.14 \pm 0.04$. If instead we adopt the mean value of the three peaks, we get $I_0 = 26.16 \pm 0.25$. The values do not differ significantly, and we conservatively adopt the latter, with its larger error.

Adjustments to the measured magnitude of the TRGB may be required due to noise, crowding, small numbers, and background contamination. Madore & Freedman assess these systematic uncertainties, and we rely on their results to determine any necessary corrections. In our sample, the typical signal-to-noise ratio in stars with $I_0 = 27$ is $\sim 35$, which is sufficient, according to Fig. 3 of Madore & Freedman, not to introduce any systematic error in the determination of the magnitude of the TRGB.

We assessed the effects of crowding by populating a blank frame with artificial stars according to a luminosity function of the form $\log N = 0.6I$ (cf. Madore & Freedman 1995), normalized to the same surface density of stars in the magnitude range $26 < I_0 < 27$ as observed in our field. We considered “blends” to be stars within 2 pixels of each other. Only 1% of stars in the magnitude interval $26 < I_0 < 27$ were blended with other stars in the same interval. 14% of stars
in this interval were blended with stars up to two magnitudes fainter. This is consistent with what we would estimate based on the surface brightness of NGC 3115 at the position of our field and the effective seeing of HST. Referring to Fig. 6 of Madore & Freedman, this suggests that the apparent magnitude of the TRGB is brighter than the true value by $\sim 0.05 \pm 0.05$ mag.

Our CMD is sufficiently well populated that we would not expect population size to introduce any uncertainty into our determination of the magnitude of the TRGB. There are $\sim 2700$ stars with $26.15 < I_0 < 27.15$ in Fig. 2. Figure 7 of Madore & Freedman implies that any systematic effects due to population size should be negligible.

Contamination from foreground stars in our own galaxy, and from globular clusters or Population I stars in NGC 3115 is negligible: both foreground stars and globular clusters are rare; only a few are expected in the entire field, and these will be much brighter than the TRGB. The main source of contamination at these magnitudes is compact galaxies. We know from the Hubble Deep Field that unresolved galaxies are predominantly blue, with $(V - I)_0 < 1.0$ (cf. Elson, Santiago & Gilmore 1996). Applying the derivatives and edge-detection algorithm only to objects redder than the dashed line in Fig. 2 gives Fig. 3c and the dotted curve in Fig. 3d. Background contamination is evidently not important in our determination of the magnitude of the TRGB.

We also checked the effect of slightly different selection lines in Figure 1a. This contributed an uncertainty of $\pm 0.05$. Thus, the main error is the photometric uncertainty of $\pm 0.12$ at $I_0 = 26.16$, and the uncertainty in isolating the point of steepest slope of the luminosity function, of $\pm 0.25$. Combining these, and
correcting our best value for crowding as above, the final value we adopt for the TRGB is $I_0 = 26.21 \pm 0.29$. Including the error of $\pm 0.10$ in the absolute magnitude of the TRGB, implies a distance modulus of $(m-M)_0 = 30.21 \pm 0.30$, corresponding to a distance of $11.0 \pm 1.5$ Mpc. This is in excellent agreement with the value $30.17 \pm 0.13$ quoted by Ciardullo, Jacoby & Tonry (1993) from the planetary nebulae luminosity function. It is $0.56$ mag greater than the value $29.65 \pm 0.25$ they quote derived from surface brightness fluctuations. The latter would imply a magnitude for the TRGB of $I_0 = 25.65$, which is inconsistent with our observations, as is apparent from an inspection of Fig. 2. We suggest, therefore, that this value may be wrong. We note however that in the sample of 16 galaxies reported in Ciardullo et al. (1993), the surface brightness fluctuation value for NGC 3115 was the most discrepant one, and is not indicative of the general accuracy of the method.

4. The Metallicity of the NGC 3115 Halo

The colour of giant branch stars is a function of their metallicity. This is illustrated in Fig. 2, where the loci of giant branches in three Galactic globular clusters (Da Costa & Armandroff 1990) are transposed to a distance modulus of 30.2 and superposed on the NGC 3115 data. The globular clusters have a wide range of metallicity: the one with the bluest giant branch, M15, has $[\text{Fe/H}]=-2.17$, the intermediate one, NGC 1851, has $[\text{Fe/H}]=-1.29$, and the reddest one, 47 Tuc, has $[\text{Fe/H}]= -0.71$. At a glance, it is clear that the halo of NGC 3115 is not very metal poor, and that it has $[\text{Fe/H}] \sim -1$. 
To determine the value more precisely, we constructed \((V - I)\) histograms in 0.2 mag intervals. These are shown in Figs. 4a-d. Here we encountered the surprising result that the colour distribution is bimodal. This is particularly evident in (c) where the sample is biggest. We fit two gaussians in the range \(1.0 < (V - I)_0 < 2.5\) allowing the amplitude, mean colour, and sigma to vary. The best values of \(< (V - I)_0 >\) in each case are plotted as large dots in Fig. 2. The bluer population is well represented by the giant branch with [Fe/H] \(-1.3\). The redder population appears to have [Fe/H] \(-0.7\). The ratio of the sizes of the blue to red populations is 1.3, 2.4, and 3.4 in the faint, intermediate, and bright bins respectively. These ratios are of course uncertain, particularly for the brighter samples, and we conclude only that the populations are of equal size to within a factor of about two. In all magnitude bins the value of \(\sigma\) for the redder population is comparable to the measurement errors, while that for the bluer population is somewhat larger than the errors. This may indicate an intrinsic spread in metallicity among the bluer population, or may be due to contamination by unresolved background sources. Our data neither contain evidence for, nor rule out, different spatial distributions for the two populations.

It is unlikely that the observed colour bimodality is due to the presence of populations with different ages. In this case, if the red population were old and metal rich (like 47 Tuc), then a younger population with the same metallicity would have to be only \(\sim 1\) Gyr old (and therefore much brighter). The presence of such a young population in the outer halo of an S0 galaxy would be difficult to explain.
5. Summary

We have presented a CMD for \( \sim 4700 \) giant branch stars in the halo of the S0 galaxy NGC 3115. The magnitude of the TRGB indicates a distance modulus of \((m - M) = 30.21 \pm 0.30\), in excellent agreement with the value \(30.17 \pm 0.13\), derived from the planetary nebula luminosity function. Our observations are not consistent with the smaller distance modulus \(29.65 \pm 0.25\) derived from surface brightness fluctuations.

The \((V - I)_0\) colour distribution of stars near the TRGB in the NGC 3115 halo is bimodal. We interpret this as indicating the presence of two distinct populations, one with \([\text{Fe}/\text{H}] \sim -0.7\) and one with \([\text{Fe}/\text{H}] \sim -1.3\). In comparison, the halo of the Milky Way has \([\text{Fe}/\text{H}] \sim -1.7\) (Ryan & Norris 1993), while the halo of M31 appears to be more metal rich, with \([\text{Fe}/\text{H}] \gtrsim -1\) (Mould & Kristian 1993; van den Bergh 1991). This is the first time such a bimodality has been observed in the stellar population of the halo of an early type galaxy, although in some cases such as M87 globular cluster systems exhibit such bimodality (cf. Ajhar, Blakeslee & Tonry 1994; Elson & Santiago 1996). Our result suggests either that NGC 3115 is the product of a merger between two galaxies of similar size, or that its halo underwent two distinct episodes of star formation, the second of which was from gas enriched by a factor of \(\sim 4\) compared to the first episode.

It would be interesting to see whether the globular cluster system of NGC 3115 reveals a corresponding colour bimodality, and also whether, with more accurate photometry, NGC 5128, another peculiar S0 galaxy, would exhibit the same effect.

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Figure Captions

**Figures 1a and b.** The parameters (a) “sharpness” and (b) the magnitude error output by ALLSTAR, plotted against $I_{814}$ magnitude for $\sim 6500$ detections in the NGC 3115 field. Crosses are artificial stars. Solid lines illustrate our selection criteria for stellar candidates. Magnitudes are from PSF fitting with a 10 pixel fitting radius.

**Figure 2.** A colour-magnitude diagram for $\sim 4700$ objects selected using the criteria illustrated in Figs. 1a and b. Magnitudes are from aperture photometry, dereddened and transformed to the Johnson-Cousins system. Most objects with $I_0 < 26$ are probably compact background galaxies. Representative Poisson error bars are shown. The two horizontal lines indicate the magnitude of the TRGB implied by the surface brightness fluctuation method and the planetary nebula luminosity function method. The curves are loci of giant branches of Galactic globular clusters transposed to a distance modulus of 30.2. They are for M15 ([Fe/H] = −2.17), NGC 1851 ([Fe/H] = −1.29), and 47 Tuc ([Fe/H] = −0.71). Large dots indicate the peaks of the histograms in Figs. 4a-c.

**Figures 3a-d.** Local slope as a function of $I_0$ of the NGC 3115 giant branch luminosity function for (a) the full sample with step sizes 0.1, 0.2, 0.3 and 0.4 mag; (b) the individual WFC chips with step size 0.2 mag; (c) the subsample redder than the dashed line in Fig. 2, with step sizes 0.1, 0.2 and 0.3 mag. (d) Output of the Sobel filter edge-detection algorithm plotted against $I_0$. The solid
curve peaking at $\sim 800$ is for the full sample, and the dashed curve is for the redder sample. The curves peaking at $< 400$ are for the individual WFC chips.

**Figures 4a-d.** Histograms of $(V - I)_0$ for three different magnitude bins. Total number of stars are (a) 316, (b) 460, and (c) 639. The vertical dashed lines indicate the peak values from Gaussian functions fitted in the range $1.0 < (V - I)_0 < 2.5$. (d) Shows the best fitting Gaussian functions for the histogram in (c). Values of $\sigma$ are 0.26 and 0.21 for the blue and red Gaussians respectively.
