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VLT deep I–band surface brightness fluctuations of IC 4296*

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Abstract. From theoretical predictions, the introduction of 8–m class telescopes permits one to extend Surface Brightness Fluctuations measurements from the ground to ≈7000 km/s, with a precision that is comparable to current space–based measure ments. We have measured I–band SBF in IC 4296 in Abell 3565 at $cz \sim 3630$ km/s with the ESO Very Large Telescope. Adopting the Tonry et al. (2000) calibration for I–band SBF we determined a distance modulus of $(\overline{I}_{o,k} - \overline{M}_I) = 33.44 \pm 0.17$ mag corresponding to a galaxy distance of 49 ± 4 Mpc. This result is consistent with the HST observation from Lauer et al. (1998): $(\overline{I}_{F814} - \overline{M}_{F814}) = 33.47 \pm 0.13$ mag.

Key words: galaxies: distances and redshifts – galaxies: individual: IC 4296

1. Introduction

I–band Surface Brightness Fluctuations (SBF) have been successfully used to measure early-type galaxy distances up to 4000 km/s from the ground and up to 7000 km/s with the Hubble Space Telescope (HST) (Sodemann & Thomsen 1995, Sodemann & Thomsen 1996, Ajhar et al. 1997, Tonry et al. 1997, Thomsen et al. 1997, Lauer et al. 1998, Pahre et al. 1999, Blakeslee et al. 1999a, Tonry et al. 2000). This method was introduced by Tonry & Schneider (1988) (a recent review has been given by Blakeslee et al. 1999a) and is based on a simple concept. The Poissonian distribution of unresolved stars in a galaxy produces fluctuations in each pixel of the galaxy image. The variance of these fluctuations is inversely proportional to the square of the galaxy distance. The SBF amplitude is defined like this variance normalized to the mean flux of the galaxy in each pixel (Tonry & Schneider 1988). The stars that contribute the most to the SBF are then the brightest stars in the intrinsic luminosity function, typically red giants in old stellar populations. The absolute magnitude of the fluctuation is not a constant, but depends on the age and metallicity of the stellar population. As such it is a strong function of not only the photometric band in which the observations are carried out, but also of the color of the galaxy under study. Tonry et al. (1997) and Tonry et al. (2000) have quantified these dependencies using an extensive sample of I and V band observations, which are used to empirically calibrate the dependence of the I-band fluctuation magnitude on (V-I) color. The absolute calibration is then obtained using a set of 5 galaxies with independent Cepheid distance. The I–band SBF absolute magnitude calibration can be written as:

$$\overline{M}_I = -1.74 + 4.5\,[(V-I)_0 - 1.15]. \tag{1}$$

Ferrarese et al. (2000a) have obtained their own calibration based on accurate Cepheid distances to six spiral galaxies with SBF measurements within 1200 km/s. The Cepheid distances were part of a larger dataset of 18 distances to galaxies within the Fornax and Virgo clusters observed by the HST Key Project on the Extragalactic Distance Scale. The two calibrations are consistent within the errors.

The potential of these measurements extends to the measurements of cosmological parameters and the study of the dynamics of the universe. SBF distances have been used in measuring the Hubble constant in the HST Key project on the Extragalactic Distance Scale (Ferrarese et al. 2000a, and references therein). Tonry and his collaborators (Tonry et al. 2000) have derived peculiar velocities from their ground based sample up to 4000 km/s and calculated bulk flows in this region. By comparing these peculiar velocities with infrared and optical surveys, Blakeslee et al. (1999a) have been able to constrain the value of the Hubble constant and the parameter density (luminous plus dark matter) $\beta = \Omega^{0.6}/b$, where b is the linear bias (Blakeslee et al. 1999b).

However, the current I–band sample is limited to 4000 km/s. The introduction of large telescopes, such as the Very Large Telescope (VLT), have opened new opportunities to extend the current sample from the ground. With the optical instrument FORS1 and FORS2 on VLT, from a theoretical point of view, it will be possible to extend I–band SBF with high signal–to–noise and good understanding of external source contribution up to ≈ 7000 km/s (Mei et al. 2000). This implies that ground–based measurements can be used to probe the same volume as HST measurements.

To illustrate the potential of I–band SBF measurements with the VLT, we have observed IC 4296 in Abell 3565. This galaxy is part of the brightest ellipticals in the Abell clusters observed

* Based on observations performed at the European Southern Observatory, Paranal, Chile; ESO program N^o 63.O-0450.

Table 1. General properties of IC 4296, from the web archive Simbad (http://simbad.u-strasbg.fr), and Lauer et al. (1998)

Name	RA	DEC	l	b	Type	m_V	$V-I$	V_{LG}
	(2000)	(2000)	deg	deg		mag	mag	km/s
IC 4296	13 36 39.46	-33 57 59.8	313.54	+27.97	E	10.57	1.24	3630

Table 2. Read out noise and gain for the four ports of FORS1 on VLT UT1

Port	FORS1 Ron (e^-)	Gain (e^-/ADU)
A	5.75±0.20	2.90±0.09
B	6.30±0.18	3.50±0.09
C	5.93±0.18	3.08±0.09
D	5.75±0.19	3.22±0.10

in the Lauer & Postman (1992) sample. An I–band SBF distance measurement of this galaxy, based on HST observations, has already been reported by Lauer et al. (1998). We compare our SBF measurements with Lauer et al. (1998) and obtain similar results and measurement precision, our errors and external source contribution estimation being comparable with HST capabilities.

2. Observations

IC 4296 was observed in service mode at the Very Large Telescope unit UT1 (Antu) at the European Southern Observatory in Paranal, Chile. The properties of this galaxy are summarized in Table 1.

I–band and V–band data were obtained to have an accurate V–I color to input in Tonry et al. (2000) calibration of I–band SBF fluctuations. The nights of observation were on 19 June and 24 July 1999 for the I–band and on 1 September 1999 for the V–band. The imaging camera was FORS1 (FOcal Reducer and low dispersion Spectrograph) with a 2048 x 2048 pixel Tektronix CCD.

The low gain, standard resolution mode, was used, with a pixel scale 0.2″/pixel and field of view 6.8′ x 6.8′. The detector had four ports with different read out noise and gain. We show the gains for the different ports in Table 2. The dark current is negligible ($< 2e^-$/pixel/hour at nominal operating temperature).

The filter was a I–band Bessel filter. The seeing was $\approx 0.7''$ FWHM on both 19 June and 24 July. The photometric zero-point and the extinction coefficient were extracted from observations of Landolt standards in the I–band Kron–Cousins (Landolt 1992). In the I–band we measure a photometric zero-point $m_1 = 25.48 \pm 0.03$ mag and an extinction coef ficient of 0.07 ± 0.015 mag. The sky brightness was on average $m^I_{sky} = 19.09$ mag/arcsec^2 on 19 June, $m^I_{sky} = 18.26$ mag/arcsec^2 on 24 July.

The raw data were galaxy exposures each of 45 seconds for a total exposure time in the I–band of 7785 seconds. They were dithered by $\approx 5''$. Individual bias subtracted and flatfield corrected frames were produced and delivered by VLT Science Operations using the VLT Data Pipeline (Hanuschick & Amico 2000). These individual frames were then combined. Bad pixels and cosmic rays were eliminated by a sigma clipping algorithm while combining the images by the IRAF task IMCOMBINE. Sub-pixel registration was not used to avoid the introduction of artificial statistics in the images. The galaxy center was in the center of the CCD. Sky estimates were done on the four corners of the CCD at $\approx 3'$ from the galaxy center.

3. Surface brightness fluctuation analysis

3.1. Measure of SBF magnitudes

The data were analyzed by the standard SBF extraction technique used e.g. by Tonry & Schneider (1988). To measure the fluctuations, a smooth galaxy profile was subtracted from to the image. It was derived by fitting galaxy isophotes to the original image, once visible external sources were subtracted. On the residual image, additional point sources were identified, using the software tool Sextractor (Bertin & Arnouts 1996) and subtracted. To account for residual sky-subtraction errors it was then smoothed on a scale ten times the width of the PSF and subtracted from the image. To make the SBF fluctuations constant across the image, the image was divided by the square root of the galaxy model. The resulting image was divided into different annuli, in each of which the power spectrum was calculated. The external point sources brigther than $m_{cut} = 24.7$ mag were masked out. A point spread function (PSF) profile was determined from the bright stars in the image and normalized to 1 ADUs^{-1}. The PSF power spectrum was then calculated. In each annulus the power spectrum of the image was calculated and normalized to the number of non-zero points in the annulus. The power spectrum was azimuthally averaged.

Two components contribute to the total image power spectrum: the constant power spectrum due to the white noise, P_1, and the power spectrum of the fluctuations and point sources that are both convolved by the PSF in the spatial domain. In the Fourier domain these latter terms are given by a constant, P_0, multiplied by the power spectrum of the PSF:

$$E_{gal} = P_0 \, E_{PSF} + P_1. \qquad (2)$$

The external source luminosity function for IC 4296 is shown in Fig. 1.

To compute P_0 and P_1, a robust linear least squares fit was made by minimizing absolute deviation (Numerical Recipes, Press et al. 1992). Low wave number points were excluded from the fit. In fact, they are contaminated by the galaxy subtraction and subsequent smoothing, as well as a residual sky variance contribution, as pointed out, i.e., by Jensen et al. (1999). The point source contribution P_{es} was estimated from the equations:

$$P_{es} = \sigma_{gc}^2 + \sigma_{bg}^2 \quad (3)$$

following, i.e., Blakeslee & Tonry (1995); σ_{gc}^2 is the contribution to the fluctuations given by globular clusters, σ_{bg}^2 is the contribution by background galaxies. We adopted the following luminosity function for the globular clusters:

$$N_{gc}(m) = \frac{N_{ogc}}{\sqrt{2\pi}\sigma} e^{\frac{-(m-m_{peak}^{gc})^2}{2\sigma^2}}, \quad (4)$$

with $\sigma = 1.35$ mag. We have fitted to our detected globular cluster number counts an initial maximum likelihood $m_{peakI}^{gc} = 25.5$ mag and have assumed an initial galaxy distance modulus 33.47 mag, from Lauer et al. (1998). From these values, we have an initial $M_{peakI}^{gc} = -7.97$ mag. This value is consistent with the $M_{peakI}^{gc} = -7.75$ mag measured by Jensen et al. (1998) in the I_{F814W} filter ($I_{KC} - I_{F814W}) \approx -0.04$ mag for $(V - I) \approx 1.25$ mag, Holtzman et al. 1995) . It is not standard according to the average $M_{peakI}^{gc} \approx -8.5$ mag, calculated from the average $M_{peakV}^{gc} \approx -7.5$ mag (Ferrarese et al. 2000b) and standard globular cluster colors (Gebhardt & Kissler-Patig 2000). This initial value was iterated in the process of the SBF distance modulus calculation. For the background galaxies, a power-law luminosity function was used:

$$N_{bg}(m) = N_{obg} 10^{\gamma m} \quad (5)$$

with $\gamma = 0.27$ (Smail et al. 1995). We kept as fixed parameters in the fit σ, γ, and m_{peak}^{gc}, iterating on the galaxy distance, while N_{ogc} and N_{obg} were estimated by fitting the composite luminosity function to the external sources extracted from the image in the range 34″ to 64″. Identified foreground stars were not included in the fit. As pointed out by Blakeslee et al. (1999a), the exact details of the adopted luminosity function for the background galaxies and the globular cluster systems have little effect on the final measurement of m_I. From the estimated N_{ogc} and N_{obg} per pixel, P_{es} was calculated as the sum of (Blakeslee & Tonry 1995):

$$\sigma_{gc}^2 = \frac{1}{2} N_{ogc} 10^{0.8[m_1 - m_{peak}^{gc} + 0.4\sigma^2 ln(10)]} \quad (6)$$
$$erfc[\frac{m_{cut} - m_{peak}^{gc} + 0.8\sigma^2 ln(10)}{\sqrt{2}\sigma}]$$

and

$$\sigma_{bg}^2 = \frac{N_{obg}}{(0.8-\gamma) ln(10)} 10^{0.8(m_1 - m_{cut}) + \gamma(m_{cut})}. \quad (7)$$

m_1 is the zero magnitude which corresponds to a flux of 1 ADUs^{-1}. A $m_{cut} = 24.7$ mag was used. The corrections were integrated over the luminosity function in each annulus, as in Sodemann & Thomsen (1995). To calculate the completeness function, simulated point source images were added to the original, galaxy subtracted image.

The SBF amplitude is given by:

$$\overline{m}_I = -2.5 log(P_0 - P_{es}) + m_1 - \epsilon_{ext} sec(z) \quad (8)$$

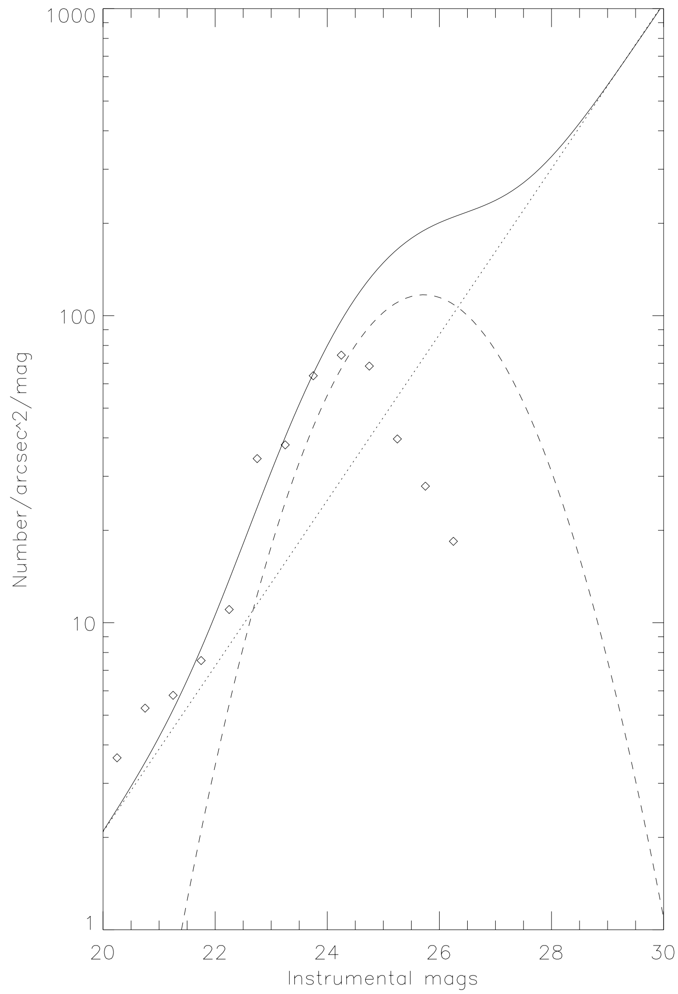

Fig. 1. We show IC 4296 external source luminosity function between 34″ and 64″. The continuous line shows the sum of the globular cluster luminosity function plus the background galaxy luminosity function. The dashed line shows the fitt ed globular cluster luminosity function, the dotted line the background galaxy luminosity function.

where ϵ_{ext} is the extinction coefficient, and z the airmass for the observations. The color term correction was negligible. We measured $\epsilon_{ext} = 0.05$ and $m_1 = 25.62 \pm 0.04$ mag. The effective airmass was $sec(z)$=1.22.

3.2. Results on IC 4296

The power spectrum fitting of IC 4296 is shown in Fig. 2. The results for each annulus are listed in Table 3. The errors on SBF magnitudes for each annulus are the standard deviations among different wavelength cuts. The errors due to external source residual contribution subtraction were added in quadrature to the fitting errors. The SBF magnitudes we calculated from Eq. 8, and the errors due to the zero point magnitude and the ϵ_{ext} were then added in quadrature.

The SBF magnitudes $I_{o,k}$ were then corrected for galactic absorption assuming $E(B-V) = 0.06$, $A_I = 1.940\, E(B-V)$, and $A_V = 3.315\, E(B-V)$, from Schlegel et al. (1998), and

Table 3. SBF measurements for various annuli of IC 4296. P_0, σ_{P_0}, P_{es} are given in units of ADU/s. The other columns are expressed in magnitudes.

Annulus (arcsec)	P$_0$	σ_{P_0}	P_{es}	$(V-I)_o$	$\overline{M}_I$	$\overline{I}_{o,k}$	$\sigma_{\overline{I}_{o,k}}$	$\overline{I}_{o,k}-\overline{M}_I$	$\sigma_{(\overline{I}_{o,k}-\overline{M}_I)}$
34 – 40	0.0068	0.0003	0.0056	1.21	-1.45	32.91	0.03	34.36	0.16
40 – 46	0.0066	0.0006	0.0048	1.22	-1.45	32.44	0.06	33.89	0.17
46 – 52	0.0088	0.0004	0.0050	1.20	-1.51	31.42	0.11	33.13	0.19
52 – 58	0.0089	0.0003	0.0038	1.18	-1.61	31.10	0.06	32.91	0.17
58 – 64	0.0083	0.0002	0.0040	1.16	-1.69	31.30	0.06	33.19	0.17
34 – 64	0.0085	0.0003	0.0054	1.19	-1.54	31.63	0.07	33.17	0.17
Mean	–	–	–	–	–	–	–	33.44	0.17

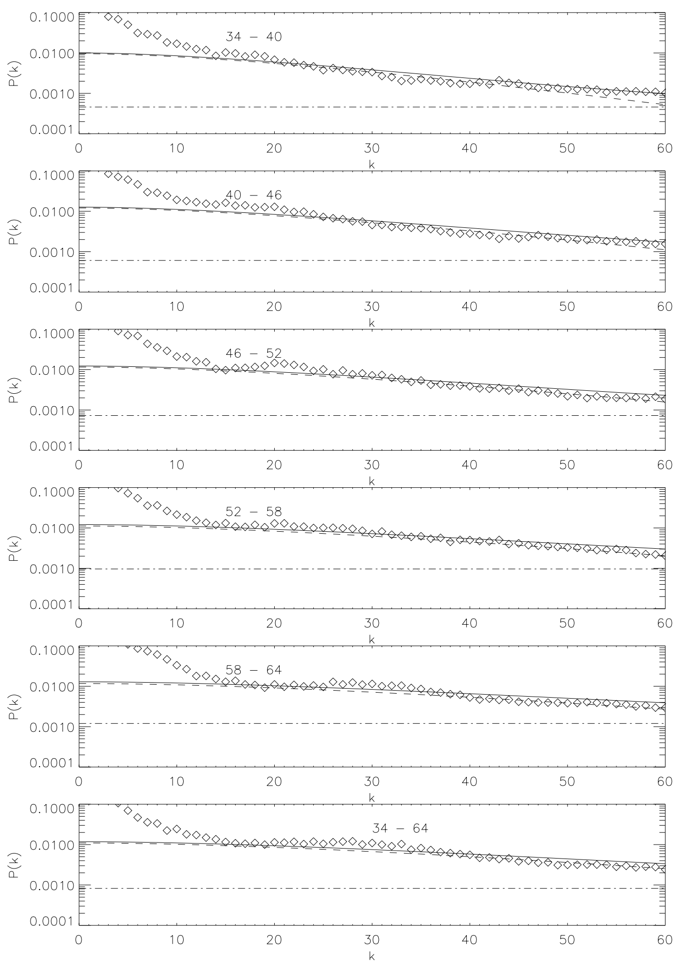

Fig. 2. IC 4296 data. We show IC 4296 power spectrum as was fitted in five different annuli of width $\approx 6''$ in the galaxy and on the full field up to 64″. The fit of the power spectrum is given by the continue line, the PSF power s pectrum by the dashed line and the dashed-dotted line is the fitted constant white noise spectrum.

a k–correction $k_I \approx 7\,z$ was applied (Tonry et al. 1997; Liu et al. 2000), $\overline{I}_{o,k} = \overline{m}_I - A_I - k_I$. The total $A_I + k_I$ was equal to 0.20 mag.

The galaxy color in each annulus is shown in Table 3. The error on each measure was 0.03 mag. The colors that are shown in the table have been corrected for extinction. The adopted $A_I - A_V$ correction amounts to 0.0825 mag.

From the Tonry et al. (2000) calibration $\overline{M}_I = (-1.74 \pm 0.08) + (4.5 \pm 0.25)\,[(V-I)_o - 1.15]$, we derive the $\overline{M}_I$ shown in Table 3. The error on each value of $\overline{M}_I$ is $\sigma_{\overline{M}_I} = 0.16$ mag.

In each annulus we derive an estimated distance modulus $\overline{I}_{o,k} - \overline{M}_I$. A mean distance modulus was determined as the mean of the values in the considered annuli. The error is given by the standard deviation of those values, around the mean, divided by the square root of the number of considered values.

The final distance modulus is $(\overline{I}_{o,k} - \overline{M}_I) = 33.44 \pm 0.17$ mag the galaxy distance 49 ± 4 Mpc. Lauer et al. (1998) have obtained $(\overline{I}_{F814} - \overline{M}_{F814}) = 33.47 \pm 0.13$ mag with a derived distance of 49 $\pm$ 3 Mpc. The two results are compatible.

The percentage error that we have on the galaxy distance is $\approx 8\%$. From the theoretical prediction given in Mei et al. (2000), we predict an error percentage of $\approx 10\%$, for a seeing $\approx 0.7''$/pixel, sky brightness $m^I_{sky} = 19$ mag/arcsec^2, and detection complete at one and a half magnitude below the peak of the globular cluster luminosity function. The two results are consistent.

4. Summary and conclusions

I–band SBF have been observed in IC 4296 with the VLT. A distance modulus of $(\overline{I}_{o,k} - \overline{M}_I) = 33.44 \pm 0.17$ mag was measured, from which a galaxy distance 49 ± 4 Mpc is derived.

This result confirms the potential of 8–m class telescopes in this kind of measurements and suggests that future SBF observations from the ground can reach the same distances that until now were only reachable by HST.

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