DETECTION OF SURFACE BRIGHTNESS FLUCTUATIONS IN ELLIPTICAL GALAXIES IMAGED WITH THE ADVANCED CAMERA FOR SURVEYS: B- AND I-BAND MEASUREMENTS¹

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ABSTRACT

Taking advantage of the exceptional capabilities of the Advanced Camera for Surveys (ACS) on board the Hubble Space Telescope (HST), we derive surface brightness fluctuation (SBF) measurements in the B and I bands from images of six elliptical galaxies with $1500 \le cz \le 3500$. Given the low signal-to-noise ratio (S/N) of the SBF signal in the blue-band images, the reliability of the measurements is verified both with numerical simulations and with experimental data tests. This paper presents the first published *B*- and *I*-band SBF measurements for distant (\geq 20 Mpc) galaxies, which are essential for comparisons of models to observations of normal ellipticals. By comparing *I*-band data with our new simple stellar population (SSP) models, we find an excellent agreement, and we confirm that I-band SBF magnitudes are mainly sensitive to the metallicity of the dominant stellar components in the galaxies and are not strongly affected by the contribution of possible secondary stellar components. As a consequence, *I*-band fluctuation magnitudes are ideal for distance studies. On the other hand, we show that standard SSP models do not reproduce the B-band SBF magnitudes of red $[(B-I)_0 \gtrsim 2.1]$ galaxies in our sample. We explore the capability of two noncanonical models in properly reproducing the high sensitivity of B SBFs to the presence of even small fractions of bright, hot stars (metal-poor stars, hot evolved stars, etc.). The disagreement is solved both by taking into account hot (post-asymptotic giant branch [AGB]) stars in SSP models and/or by adopting composite stellar population models. Finally, we suggest a limit value of the S/N for the B-band SBF signal required to carry out a detailed study of stellar population properties based on this technique.

Subject headings: galaxies: elliptical and lenticular, cD — galaxies: evolution — galaxies: photometry galaxies: stellar content

1. INTRODUCTION

The first applications of the SBF technique were mainly devoted to refining the method itself and to gauging distances of elliptical galaxies and bulges of spirals up to ~ 20 Mpc (e.g., Tonry & Schneider 1988; Tonry et al. 1989, 1990; Tonry 1991; Jacoby et al. 1992). A deeper understanding of the SBF technique, together with technological improvements of telescopes, made it possible to extend the method to distances as far as ~ 100 Mpc (Jensen et al. 2001) with uncertainties typically lower than 10%, and to measure luminosity fluctuations for a wider family of astronomical objects ranging from Galactic and Magellanic Cloud globular clusters (Ajhar & Tonry 1994; González et al. 2004; Raimondo et al. 2005, hereafter R05) to dwarf ellipticals (Jerjen et al. 1998, 2000; Mieske & Hilker 2003), in addition to the usual targets (elliptical galaxies and bulge spirals).

In their seminal paper Tonry & Schneider (1988) suggested that it was also possible to take advantage of SBFs in order to analyze the metallicity and age of the stellar system in the galaxy. Such a connection was revealed through the correlation between the SBF amplitudes and the integrated color of the galaxy. This behavior, effectively detected only after a substantial number of

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measurements was available (Tonry et al. 1990), on one hand showed that to obtain reliable SBF-based distances, SBF versus integrated color relations must be used to "standardize" the SBF absolute magnitude. On the other hand, it also emphasized the possible use of the SBF as a tracer of stellar population properties.

The link between SBFs and stellar populations is easily understood considering that, given the image of a galaxy, the SBF signal rises from the statistical fluctuation between adjacent regions, due to the finite number of stars per resolution element. In particular, the SBF is defined as the spatial fluctuation of the galaxy surface brightness, normalized to the surface brightness itself. As demonstrated by Tonry & Schneider, by definition the SBF amplitude corresponds to the ratio of the second to the first moments of the luminosity function of the underlying stellar system. This means that for a typical stellar population of an earlytype galaxy composed mainly by old and metal-rich stars ($t \gtrsim 5$ Gyr, $[Fe/H] \gtrsim -0.3$, the SBF nearly corresponds to the average magnitude of the red giant branch (RGB) stars in the population. In this view-keeping in mind that stellar systems with different metallicities and ages have different RGBs and thus different SBFs-the connection between SBFs and stellar populations is clear.

In order to use SBF measurements to analyze the age and chemical composition of stellar systems, when individual stars cannot be resolved there are two facts to be considered. First, on the observational side, in addition to the apparent SBF magnitude an estimation of the galaxy distance is needed so that the absolute SBF magnitude can be derived; otherwise, SBF color or SBF gradient data, which are distance-independent, are needed. Second, theoretical values for the absolute SBF magnitudes must be available.

The theoretical study of fluctuation amplitudes has been widely explored in the last decade, typically using SSP models. Since

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Observational Data							
Galaxy (1)	R.A. (J2000.0) (2)	Decl. (J2000.0) (3)	(km s^{-1}) (4)	<i>T</i> (5)	$\begin{array}{c} A_B \\ (6) \end{array}$	F814W Exp. Time (s) (7)	F435W Exp. Time (s) (8)
NGC 1407	55.052	-18.581	1627	-5	0.297	680	1500
NGC 3258	157.226	-35.606	3129	-5	0.363	2280	5360
NGC 3268	157.503	-35.325	3084	-5	0.444	2280	5360
NGC 4696	192.208	-41.311	3248	-4	0.489	2320	5440
NGC 5322	207.315	60.191	1916	-5	0.061	820	3390
NGC 5557	214.605	36.494	3433	-5	0.025	2400	5260

TABLE 1

NOTES.—Col. (1): Galaxy name. Cols. (2) and (3): Right ascension and declination from RC3; units of right ascension are hours, and units of declination are degrees. Col. (4): Recession velocity in the CMB reference frame from Tonry et al. (2001). Col. (5): Morphological T type from RC3. Col. (6): *B*-band extinction from Schlegel et al. (1998). Cols. (7) and (8): Total exposure time for F814W and F435 images, respectively.

Tonry et al. (1990), many other authors (e.g., Buzzoni 1993; Worthey 1993a; Blakeslee et al. 2001, hereafter BVA01; Liu et al. 2000; Cantiello et al. 2003; Mouhcine et al. 2005; R05; Marín-Franch & Aparicio 2006) explored a wide range of metallicities (0.0001 $\leq Z \leq 0.05$) and ages (20 Myr $\leq t \leq 18$ Gyr), in various wavelength intervals. These models showed a general agreement, although they are based on quite different input stellar physics. A general conclusion drawn from all models is that SBF magnitudes at shorter wavelength intervals—e.g., in the *B* band—show a stronger sensitivity to the chemical composition and age with respect to other bands; thus, they must be preferred to address stellar population studies. This is particularly interesting in objects such as elliptical galaxies, where dust pollution (which strongly affects bluer bands) is negligible or recognizable as irregular spots in the otherwise regular galaxy profile.

Up to now, the few examples on the use of SBFs to probe the unresolved stellar content of galaxies have been based mainly on the comparison with models of the absolute fluctuation magnitudes \bar{M}_{λ} in a certain wavelength interval $(\lambda, \lambda + \Delta\lambda)$, thus relying on some assumption of the galaxy distance. There are fewer studies based on SBF color data, due to the general lack of multiwavelength SBF data for the same galaxy. One recent application to galaxies is the work by Jensen et al. (2003), which couples ground-based *I*-band SBFs with near-IR (F160W) *HST* data. Finally, only a few works have presented SBF radial gradients within galaxies (Tonry 1991; Sodemann & Thomsen 1995; Tonry et al. 2001; Cantiello et al. 2005, hereafter C05).

The aim of this paper is to present a set of *B*- and *I*-band SBF measurements for a selected sample of galaxies imaged with the ACS on board the *HST*. In C05 we succeeded in revealing M_I radial ($10'' \leq r \leq 40''$) gradients within seven early-type galaxies. For six of these galaxies, F435W (~Johnson *B* band) images are also available. Taking advantage of the capabilities of the ACS, in this paper we present the SBF analysis for the *B* images, whose SBF signal is expected to be substantially fainter than in the *I*-band images. To produce a homogeneous set of measurements for both bands, we repeat the SBF analysis also for *I*-band data, adopting the same constraints (masks, regions for the SBF measurements, etc.) as for the *B* images.

The paper is organized as follows. Section 2 describes the selected sample of objects, the procedures adopted to derive the surface photometry, the photometry of pointlike and extended sources, and the SBF magnitudes. In § 3 we introduce some tests performed to check the quality of our SBF measurements on *B*-band frames. The analysis of some observational properties of the galaxies sampled (plus two more objects whose data are taken from the literature) and the comparison of data with models are presented in § 4. We finish this paper with conclusions, given in § 5.

2. DATA REDUCTION AND ANALYSIS

2.1. Observations

Five of the galaxies considered here were presented in C05 (NGC 1407, NGC 3258, NGC 3268, NGC 5322, and NGC 5557), while NGC 404 and NGC 1344 were excluded because no F435W images are available. The raw data are ACS F435W and F814W exposures drawn from the *HST* archive. All data are taken with the ACS in its Wide Field Channel mode. The observations are deep exposures associated with proposal ID 9427, which was designed to investigate the globular cluster system for a sample of 13 giant ellipticals in the redshift regime $1500 \le cz \le 5000$. Among these galaxies, we selected six objects less polluted by dust patches and with exposure times long enough to allow SBF measurements. Table 1 summarizes some properties of the galaxies sampled together with the exposure times in each filter.

As in C05, the image processing (including cosmic-ray rejection, alignment, and final image combination) is performed with the Apsis data reduction software (Blakeslee et al. 2003). The ACS photometric zero points and extinction ratios are from Sirianni et al. (2005, hereafter S05), along with a correction for Galactic absorption from Schlegel et al. (1998). Because of the small quantity of dust in normal elliptical galaxies, no internal extinction correction has been considered here. The dusty patches present in the case of NGC 4696 can be easily recognized in the *B*-band images and have been masked out. For this galaxy the percentage of the image area masked for dust is <2% of the whole ACS field of view (or <8% of the final area selected for SBF measurement).

To transform the ACS photometry to the standard *UBVRI* photometric system, we use the equations from S05. For the *B*- and *I*-band data, the average difference between the ACS magnitudes and the ones obtained after applying the S05 equations does not exceed 0.03 mag. In C05 we presented some consistency checks of the (F435W, F814W) to (*B*, *I*) transformations by comparing, for each galaxy, the transformed magnitudes and colors with available measurements taken in the standard photometric system. The results of the comparisons supported the reliability of S05 equations for the selected filters (see C05 for more details).

2.2. Data Analysis

The procedure adopted to derive SBF measurements from the *B*-band frames is the same as that described in C05, with minor changes that will be discussed below, together with a brief summary of the whole procedure.



FIG. 1.— Upper plots: Number of sources detected (globular clusters + galaxies) brighter than the magnitude m_{fix} , vs. the magnitude m_{fix} itself. We defined the latter quantity as the average magnitude of the sources detected for the specific σ_{DT} adopted. The left (right) panel exhibits the results of this test for *B*-band (*I*-band) simulations. Filled circles refer to the total number of objects detected on the frame simulated; the solid line shows the input total integrated LF adopted for the simulations. Lower plots: Differences between the number of detected objects brighter than m_{fix} and the real number of objects adopted for the simulation: $\Delta N = |N_{detected} - N_{input}|$.

2.2.1. Galaxy Modeling and Sky Subtraction

Galaxy light-profile modeling and subtraction, sky subtraction, and source masking proceeded in an iterative way. In brief, a provisional sky value for the whole image is assumed to be equal to the median pixel value in the corner with the lowest number of counts. After this sky value has been subtracted from the original image, we started an iterative procedure where (1) the fit of the median galaxy profile is obtained using the IRAF/STSDAS task ELLIPSE; (2) all the foreground stars, background galaxies, and the galaxy's globular clusters (hereafter referred to as external sources) detected in the sky+galaxy subtracted frame are masked out; and (3) a new sky value is obtained by fitting a $r^{1/4}$ law to the surface brightness profile of the galaxy.

The procedure is then repeated; each time, the ellipse fitting is performed using the updated mask of external sources, until convergence. As shown in C05, the uncertainty of assuming a $r^{1/4}$ profile instead of a $r^{1/n}$ or a Nuker profile does not significantly alter the final value of integrated and SBF magnitudes, at least in the regions where the galaxy's signal is higher than the background. The galaxy counts in the regions where the SBF color measurements were made are on average a factor of ~ 7 (~ 17) higher than the sky level in the *B*(*I*) images.

2.2.2. Photometry of Pointlike and Extended Sources

Once the sky and the galaxy model were subtracted from the original image, we derived the photometry of the external sources. The construction of the photometric catalog of pointlike and extended sources is critical for the estimation of the luminosity function (LF). As is shown in C05, by fitting the LF of external sources (i.e., of globular clusters and background galaxies) we can infer, by extrapolation, its faint end, which must be determined in order to have reliable SBF measurements. This is due to the fact that the fluctuations measured from the sky+galaxy subtracted frame also include a contribution arising from the undetected external sources left in the image. A reliable LF model allows one to properly estimate and subtract such residual fluctuation (usually indicated as P_r) from the total fluctuation signal, P_0 .

To obtain the photometry of external sources, we used the software SExtractor (Bertin & Arnouts 1996), as it gives good photometry of both pointlike and extended objects. It also gives as output a smoothed background map, which is essential to remove the large-scale residuals from the galaxy-subtracted frame. Moreover, it accepts user-specified weight images, and this is of great importance for our measurements, as, by specifying the error map, the photometric uncertainty can be estimated by taking into account the contribution to the noise due to the subtracted galaxy. We have modified the SExtractor input weight images by adding to the rms image the galaxy model times a constant factor of ~ 0.5 for *B*-band images and of ~ 1 for *I*-band images. The constant factors have been chosen, after several checks, so that the surface brightness fluctuations are recognized as noise (Tonry et al. 1990); lower coefficient values would result in the detection and masking of fluctuations as external sources. On the contrary, higher values would result in many real external sources being undetected and would therefore affect the SBF measurement.

We ran SExtractor on the residual images (i.e., galaxy+sky+ large-scale residual subtracted images) independently for each band. The best parameters for source detection have been chosen by using numerical simulations. In particular, we have simulated images with known input LFs, and then the simulated images were analyzed in the same way as real frames, to study the LFs of the sources detected. Finally, the input LFs have been compared with the ones derived from our standard analysis of the frame.

As an example of this procedure, in Figure 1 we show the derived best fit of the LF of external sources obtained in order to determine the optimal detection threshold (DETECT_THRESH, hereafter σ_{DT}) SExtractor parameter.⁶

In particular, we changed σ_{DT} within the interval 0.5–50, obtaining different photometric catalogs, each one characterized by

⁶ We have used a fixed DETECT_MINAREA ~ 5, corresponding to the point-spread function (PSF) area of our ACS images. The SExtractor detection S/N limit is $\sigma_{\text{DT}} \times (\text{DETECT}_MINAREA)^{1/2}$. For this test we have used the images simulated according to prescriptions presented in § 3. This allowed us to compare the observed integrated LF with the input one.



FIG. 2.—*B*-band (*left plots*) and *I*-band (*right plots*) total LF of external sources. The panels show the observed total number density as a function of the magnitude (*squares*) and the model LF used to estimate the residual contribution to fluctuations arising from undetected sources (*solid line*). The two components of the model number density, globular clusters and background galaxies, are also shown with dashed and dotted lines, respectively.

the number of sources detected in both frames and by the average magnitude of the sources detected, $m_{\rm fix}$. By lowering the $\sigma_{\rm DT}$, one has correspondingly (1) an increasing number of sources detected; (2) a fainter average magnitude detected, $m_{\rm fix}$; and (3) an increasing number of spurious detections. In Figure 1 we plot with filled circles the total observed number ($N_{\rm detected}$) of detected sources brighter than $m_{\rm fix}$ versus $m_{\rm fix}$ for the *B* band (*top left panel*) and the *I* band (*top right panel*). The solid line in these panels shows the input total number of sources ($N_{\rm input}$). The lower panels show the residuals, i.e., $\Delta N = |N_{\rm detected} - N_{\rm input}|$. We have chosen as a final detection parameter $\sigma_{\rm DT} = 1.3$, as, for this value, ΔN remains below 50 for both *I*-band and *B*-band frames, i.e., below ~5% of the total number of sources detected (for a high number of detections).

The final photometric catalogs of external sources from *B*- and *I*-band images were matched using a radius of 0.1". On average, the number of objects clearly detected in the *I*-band frame and undetected in the *B*-band frame in, e.g., red galaxies, is ≤ 30 . We have verified that including the photometry of these missing objects does not significantly alter the LF model, and therefore the correction to the SBF signal for undetected sources is not significantly changed.

Once the catalog of matched sources was constructed, we applied the aperture correction as in C05. That is, for pointlike sources we derived the aperture correction by making a growth-curve analysis over a few bright, well-isolated point sources in the frame (Stetson 1990). The aperture correction was obtained by summing the contribution evaluated from the growth-curve analysis, with aperture diameters of 6–20 pixels and the contribution from 20 pixels to "infinite" diameter reported by S05. For extended sources, we used the aperture correction following the prescriptions by Benítez et al. (2004).

A model LF was then derived from the final photometric catalog by assuming the total number density to be the sum of a Gaussian-shaped globular cluster LF (GCLF; Harris 1991),

$$n_{\rm GC}(m) = \frac{N_{0,\rm GC}}{\sqrt{2\pi\sigma^2}} \ e^{-(m-m_{\lambda,\rm GC})^2/2\sigma^2},$$
 (1)

and a power-law LF (Tyson 1988) for the background galaxies,

$$n_{\rm gxy}(m) = N_{0,\rm gxy} 10^{\gamma m},\tag{2}$$

where $N_{0,GC}$ ($N_{0,gxy}$, Blakeslee & Tonry 1995) is the globular cluster (galaxy) surface density, and $m_{\lambda,GC}$ is the turnover magnitude of the GCLF at the galaxy distance. In expression (2) we used the γ -values obtained by Benítez et al. (2004). For the GCLF we assumed the turnover magnitude and the width of the Gaussian function from Harris (2001). To fit the total LF we used the software developed for the SBF distance survey; we refer the reader to Tonry et al. (1990) and Jacoby et al. (1992) for a detailed description of the procedure. In brief, a distance modulus (μ_0) for the galaxy is adopted in order to derive a first estimation of $m_{\lambda,GC} = \mu_0 + M_{\lambda,GC}$, then an iterative fitting process is started with the number density of galaxies and GCs, and the galaxy distance is allowed to vary until the best values of $N_{0,GC}$, $N_{0,gxy}$, and $m_{\lambda,GC}$ are found via a maximum likelihood method.

Figure 2 exhibits the observed *B*- and *I*-band LFs for the whole sample of galaxies, as well as their best-fit curves. In this figure we report the LF over the entire area analyzed, although the SBF analysis is conducted independently in annuli (Tonry et al. 1990).

The source catalog is then used to mask all sources brighter than a (radially dependent) completeness limit. The residual fluctuation amplitude due to the remaining undetected faint sources, P_r , is then evaluated as described in C05.

As shown in Table 2, *I*-band SBF magnitudes are not strongly affected by the P_r correction, which is typically a factor of 20 smaller than the stellar fluctuation amplitude, P_f . The case of *B*-band SBFs is quite different. In this case, the amplitude of the stellar SBF competes with the residual variance from undetected sources. For *B*-band measurements, in fact, we find an average $P_r \sim 0.22P_f$. However, even in the case of *B*-band data, the accuracy of the photometric catalog allowed us to obtain a reliable LF model.

In order to estimate the uncertainty associated with P_r , we have carried out several numerical experiments by using the tool described in § 3. In particular, we have estimated P_r from simulations

TA	BLE 2
Fitting	PARAMETERS

	<i>r</i>	B-BAND FITTING PARAMETERS (ADU PER EXPOSURE)				I-BAND FITTING PARAMETERS (ADU PER EXPOSURE)					
Galaxy (1)	(arcsec) (2)	<i>P</i> ₀ (3)	<i>P</i> ₁ (4)	<i>P_r</i> (5)	<i>P</i> _f (6)	S/N (7)	P ₀ (8)	<i>P</i> ₁ (9)	<i>P_r</i> (10)	<i>P</i> _f (11)	S/N (12)
NGC 1407	13 3 26	0.67 ± 0.02	0.17	0.22	0.45	2.6	3.93 ± 0.07	0.14	0.29	3.64	25
NGC 3258	13 6 20	0.99 ± 0.10	0.19	0.39	0.59	3.2	5.61 ± 0.20	0.12	0.27	5.34	43
NGC 3268	12 6 20	0.85 ± 0.11	0.16	0.40	0.46	2.9	5.72 ± 0.08	0.11	0.25	5.46	49
NGC 4696	14 6 20	0.84 ± 0.13	0.11	0.42	0.43	4.0	5.30 ± 0.19	0.07	0.26	5.04	73
NGC 5322	15 6 26	0.94 ± 0.05	0.21	0.10	0.84	4.0	4.43 ± 0.06	0.18	0.18	4.26	23
NGC 5557	12 3 20	0.93 ± 0.04	0.14	0.12	0.81	5.7	5.37 ± 0.20	0.13	0.18	5.19	40

NOTES.—Col. (1): Galaxy. Col. (2): Average annular radius, innermost mask radius, outermost mask radius. Cols. (3)–(6): P_0 , P_1 , P_r , and P_f , estimated for *B*-band images. Col. (7): S/N evaluated as $(P_0 - P_r)/P_1$ for *B*-band frames. Cols. (8)–(11): P_0 , P_1 , P_r , and P_f , estimated for *I*-band images. Col. (12): S/N for *I*-band frames.

of ACS images having similar properties to our real images and compared it with the known input value. We found that a realistic estimation of the P_r uncertainty is ~20% the value of P_r . In addition, we have also estimated that changes of up to 50% of the original value in the LF fitting parameters (γ , $M_{\lambda,GC}$, etc.) affect the final P_r by less than 15%. In conclusion, we adopt 20% of P_r as an estimate of its uncertainty.

2.2.3. SBF Measurements

The SBF analysis executed for *B*-band frames is similar to the one described in C05, except for the fact that here we derive one single SBF value per galaxy (instead of different SBF measurements in several concentric annuli as in C05), since *B*-band images do not achieve a sufficiently high S/N to make a detailed study of the fluctuation amplitude as a function of radius.

For the sake of homogeneity we also reanalyzed *I*-band images by adopting the same annuli shape as from the *B* frames. The annulus was created using a mask that matches the ellipticity and position angle of a given region. All frames were analyzed in the same way. After subtracting the sky, the galaxy model, and the large-scale residuals, we derived (1) the photometry of point-like and extended sources in the frame, masking (2) all sources above a fixed S/N ratio (~3.0). Afterward, the residual frame divided by the square root of the galaxy model was Fourier-transformed, and (3) the azimuthal average of the power spectrum P(k) was evaluated. Then we derived (4) the constants P_0 and P_1 in the equation

$$P(k) = P_0 E(k) + P_1,$$
 (3)

adopting a robust linear least-squares method (Press et al. 1992). In the latter equation E(k) is the azimuthal average of the convolution between the PSF and the mask power spectra. The PSF used was the template PSF from the ACS Instument Design Team (IDT), constructed from bright standard-star observations. Finally, the SBF amplitude in magnitude was

$$\bar{m} = -2.5 \log(P_0 - P_r) + \max_0 - A_\lambda,$$
 (4)

where P_r is the residual variance due to unmasked sources in the frame, which has been estimated from the LF of the external sources detected in the frame (§ 2.2.2; see also C05). The constant mag₀ is the zero-point magnitude from S05, while A_{λ} is the extinction correction.

To test the stability of these measurements, we performed several tests. As an example, we have chosen a few well-isolated point sources available in the frames, repeating the fitting operations for equation (3) using these new objects as PSF references. The resulting SBF magnitudes agree with the previous measurements within uncertainties. The final P_0 , P_1 , P_r , and P_f values are reported in Table 2, while the SBF magnitudes and $(B - I)_0$ color are reported in Table 3, together with other properties of the galaxies. The SBF error estimates include (1) the error in the determination of P_0 , (2) a ~5% error from the PSF (C05), and (3) the uncertainty of P_r , all summed in quadrature. As shown in C05, the effect on SBFs arising from sky uncertainty is negligible.

The distance moduli reported in Table 3 are derived by averaging the group distance moduli estimations of fundamental plane and *Infrared Astronomical Satellite (IRAS)* velocity-map distributions (see Table 6 of C05). For NGC 5557, since no group distance is known, we adopted the weighted average distance estimations for the galaxy itself. M32 distance is derived as weighted averages of group distances from the Ferrarese et al. (2000) database, excluding SBF-based distances. NGC 5128 distance comes from the recent Ferrarese et al. (2007), based on Cepheid variables.

3. CHECKS ON SBF MEASUREMENT RELIABILITY

As discussed in Jensen et al. (1996) and Mei et al. (2001), in order to obtain reliable SBF measurements in the IR, the S/N \equiv $(P_0 - P_r)/P_1 = P_f/P_1$ must be $\gtrsim 5$. The conclusions of these authors agree with Blakeslee et al. (1999), who, from an observational point of view, provided the equation to predict the SBF S/N ratio, suggesting that this value be kept above 5–10. As shown in Table 2, the *I*-band S/N measured from our data is $\gtrsim 20$, while for *B*-band images it can be as low as ~ 2.6 , and it is ~ 5.7 in the best case. In this section we present various consistency tests useful for verifying the reliability of our SBF measurement procedure in such low S/N regimes.

As a first check, we developed a procedure capable of simulating realistic CCD images of galaxies with known input SBF magnitudes derived using SSP models; then we measured the SBF of the simulated image to verify the matching with the input SBF value. In order to properly simulate the properties of our real images, the simulations also included external sources and the instrumental noise of the camera. A detailed description of the simulations is reported in the Appendix.

To check the consistency of the measured SBF signal with the input one as a function of the S/N of the image, we have performed two different tests, adopting two distance moduli for the galaxy ($\mu_0 = 32, 33$), changing the exposure time in a wide range for each distance modulus. To properly take into account

9	45

$ar{m}_{I,0}$ (6)
31.08 ± 0.07
31.95 ± 0.06
31.90 ± 0.06
31.99 ± 0.07
31.22 ± 0.07
32.17 ± 0.08
22.78 ± 0.04
26.05 ± 0.11

TABLE 3	
OBSERVATIONAL DATA	

Notes.—Col. (1): Galaxy name. Col. (2): Distance modulus derived averaging the group μ_0 estimations of fundamental plane and *IRAS* velocity-map distribution (see Table 6 in C05). For NGC 5557 no group distance is known, so we adopt the weighted average distance of various μ_0 estimated for the galaxy itself. M32 distance is derived as weighted averages of group distances from the Ferrarese et al. (2000) database, excluding SBF-based distances. NGC 5128 distance comes from Ferrarese et al. (2007) based on Cepheid variables. Col. (3): Apparent total *B* magnitude and uncertainty from the HyperLeda catalog (http://leda.univ-lyon1.fr). Col. (4): $(B - I)_0$ integrated color. Cols. (5) and (6): *B*- and *I*-band SBF apparent magnitudes.

the role of the P_r correction, we have assumed the LFs of globular clusters and background galaxies according to the average properties of our ACS images. The results of this study are reported in Figure 3. In this figure we show the input SBF magnitudes (*hatched areas*; models are from the Teramo SPoT group⁷), the SBF measured in the simulated frame before adding external sources (*stars*), and the SBF magnitudes measured after including also external sources (*circles*). From these panels we can recognize that the measured SBFs agree with the input signal within uncertainty, but the uncertainty strongly increases at low exposure times, i.e., low S/N, since the residual sources P_r and the white-noise P_1 components dominate the total fluctuation amplitude. The properties of the observational data used for this work are also shown in

 $^7\,$ The Teramo Stellar POpulations Tools (SPoT) models, from R05, are available at http://www.oa-teramo.inaf.it/SPoT.

Figure 3 with boxes located in the regions corresponding to the proper exposure times (only objects at the correct distance have been considered for each panel). In conclusion, these simulations show that our SBF measurement procedure works well on CCD images having *average* properties similar to our sample of ACS images. However, it must be pointed out that each single galaxy of the present sample has different characteristics (amount of external sources, effective area for the SBF analysis, etc.), which can affect the SBF estimation in each specific case.

As a further check of the measurement quality, we have obtained SBF measurements versus the exposure time for real data by degrading the original high-S/N images to simulate a shorter exposure time and smaller SBF S/N. For this test we have used NGC 5557 data, splitting the images of both bands available in three different exposure times: total (S/N \leq 6), 2/3 total (S/N \leq 4), and 1/2 total (S/N \leq 3) exposure times. As a result, we find that



FIG. 3.—Left: Absolute SBF magnitudes measured for the galaxy simulated at distance modulus $\mu_0 = 32$ against the exposure time adopted for the simulation. Stars mark the SBF measured from the frame without external sources; i.e., the P_r term is zero $(1 - \sigma \text{ area is also shown with long-dashed lines})$. Circles mark the SBF measured from the final image: it is shown that adding external sources causes a higher dispersion of data and higher uncertainties at lower exposure times. The hatched horizontal area refers to the input SBF signal. Finally, the boxes locate the positions of our observational data for those galaxies at $\mu_0 \sim 32$. Right: Same as the left panel, but for $\mu_0 = 33$.

the *I*-band SBF measurements are left practically unchanged, as there is less than a 0.1 mag difference between the two extreme exposure times. On the contrary, the *B*-band image with the lowest exposure time (S/N < 3) has a too bright SBF, as $\bar{m}_B \sim 34.6 \pm$ 0.3 compared to the original $\bar{m}_B \sim 35.2 \pm 0.3$. Both *B*- and *I*-band SBF amplitudes measured from the 2/3 exposure time frames agree within uncertainty with the original measurement.

In conclusion, we adopt the value S/N \sim 3 as a limit of separation between unreliable and reliable SBF measurements for F435W ACS images. With this choice, we are led to consider as reliable (within the quoted uncertainties) the *B*-band SBF data for NGC 4696, NGC 5322, and NGC 5557, while NGC 3258 and NGC 3268 both lie on the limit of reliability and NGC 1407 is below it. In the following sections, the *B*-band SBF measurement for the last three galaxies will be quoted but not considered in the analysis and discussion.

4. DISCUSSION

The common use of SBF magnitudes as a distance indicator relies on the tight dependence of fluctuation amplitudes on the properties of stellar populations in galaxies. However, SBF brightness dependence on stellar population depends on the wavelength interval considered. Theoretical studies have shown that the SBF measured in filters such as *B* are not good distance indicators because one parameter (i.e., integrated color) is not sufficient to describe the stellar population of galaxies, but they are appropriate for stellar population analysis. As discussed by several authors (e.g., Worthey 1993b; Sodemann & Thomsen 1996; Cantiello et al. 2003; R05), *B*-band SBF magnitudes can be strongly affected by the light coming from hot luminous stars (extreme horizontalbranch [HB], post-AGB, young main-sequence [MS] stars, etc.).

The limited number of observational data in the *B* band up to now hampered the ability to check the validity of model SBF predictions. Furthermore, the available data mainly refer to galaxies at distances lower than 5 Mpc: M32 (Sodemann & Thomsen 1996) and NGC 5128 (Shopbell et al. 1993). These two galaxies will be added to our sample of objects in § 4.1. The \bar{m}_I value for NGC 5128 comes from the Tonry et al. (2001) database. All the data adopted for M32 and NGC 5128 are reported in Table 3. The $(B - I)_0$ color for these galaxies is obtained using the C05 color transformations, upgraded with the new R05 models.

The measurements presented in this paper increase the sample of *B*-band SBF data, and they are the first for a sample of distant giant elliptical galaxies. Within the limits of the low S/N of the *B*-band SBF data, in the following sections we compare *B*- and *I*-band SBF magnitudes and colors with model predictions, in order to point out the capabilities of blue-band SBFs as an inquiry tool for stellar populations, especially in view of applications (\bar{B} radial gradients, \bar{B} near-IR color data, etc.) based on future high-S/N imaging data.

4.1. Observational Properties and Comparison with Standard SSP Models

In this section we discuss some characteristics of the SBF data for our sample of objects in light of the most recent and detailed SBF model predictions. It is important to emphasize that the forthcoming comparison is only a "first approximation" approach to the general problem of inferring the physical properties of the stellar populations generating the SBF signal.

As a first step, we make use of upgraded and reliable R05 models that—within the same consistent theoretical framework—have been proven to reproduce in detail the color-magnitude diagrams, the integrated magnitudes and colors, and SBFs of well-studied systems (e.g., Galactic globulars and Magellanic



FIG. 4.—Observational data compared with models for various chemical compositions (see the labels in the upper plot), with ages 1.5, 2, 3, 4, 5, 7, 9, 11, 13, and 14 Gyr (symbols with increasing size mark models of older age). Models are from the SPoT Web site (R05). Filled (open) circles mark the location of our ACS *B*-band reliable (unreliable) SBF measurements. Triangles show the location of M32 and NGC 5128. M32 and NGC 5128 $(B - I)_0$ error bars are evaluated taking into account the uncertainties of the $(B - I)_0$ to $(V - I)_0$ color transformation.

Cloud star clusters) and elliptical galaxies. Even so, one should keep in mind that SBF predictions include the uncertainties and assumptions (initial mass function [IMF], color transformation, evolutionary tracks, etc.) that typically affect the theoretical stellar population synthesis models. Thus, taking into account the observational uncertainties and the small number of galaxies observed, the present discussion should be considered as an exploration of the capabilities of the SBF method in the *B* band more than a detailed comparison of models with data.

In Figure 4 we compare SBF and color data with the recent R05 SSP models. The top two panels in Figure 4 show the M_I and M_B versus the galaxy integrated color. Absolute SBF magnitudes are derived using the distance moduli reported in Table 3. SBF color data and models are shown in the bottom panel. In this figure we plot with different symbols the reliable data (*filled circles*) and the *B*-band unreliable data (*open circles*). The data of M32 and NGC 5128 are also reported (*triangles*). For completeness and, additionally, to emphasize possible inhomogeneities emerging between the different bands, in the following paragraphs we analyze the galaxy properties emerging from each of the panels in Figure 4.

 M_I versus $(B - I)_0$.—I-band comparison of the models to the data shows excellent agreement of R05 SBF models with SBF measurements. This result substantially supports the finding presented in C05, although here we are discussing one single averaged SBF measurement instead of SBF gradients. Specifically, an old, $t \gtrsim$ 10 Gyr, metal-rich $Z \gtrsim 0.02$ stellar population dominates the light emitted by these galaxies.

For the case of M32, SBF data are well reproduced by R05 SSP models with an age of ~5 Gyr and $Z \leq 0.02$. This result is very similar to that found by Cantiello et al. (2003) and by other authors (e.g., Trager et al. 2000) from line-strength analysis.

NGC 5128 (Centaurus A) data are consistent with SSP models having $t \gtrsim 3$ Gyr and $Z \lesssim 0.02$. The average metallicity inferred from resolved halo stars is $Z \gtrsim 0.005$, with a large spread; two age peaks are recognized, one at 2 Gyr and one at older ages (Marleau et al. 2000). Moreover, the complexity of the NGC 5128 stellar system increases as one approaches the regions of the dark absorption lanes in the galaxy (Rejkuba et al. 2001). Note that the resolved star data refer to regions not overlapping with the SBF data measured closer to the center of the galaxy. Broadband colors in regions overlapping ours have been derived by several authors (van den Bergh 1976; Dufour et al. 1979). These authors settled the two-fold character of the NGC 5128 stellar populations, with a main body component that is old but bluer than usual in elliptical galaxies, consistent with a 7-9 Gyr, $Z \sim 0.01$ stellar system and a disk of young, metal-rich stars. In conclusion, taking into account the complexity of the stellar system of NGC 5128, and the integrated nature of the SBF signal data, we consider as satisfactory the agreement between the properties of stellar systems inferred from SBF versus color data/ model comparisons and properties taken from literature.

 \overline{M}_B versus $(B - I)_0$.—Inspecting the middle panel of Figure 4 we find that the *B*-band SBF magnitudes are brighter than the model predictions, in contrast to the good agreement obtained with the *I* band. The only exception is NGC 5128 (and NGC 3268, which, however, we consider at the limit of reliability), due to the large error bars. All the galaxies at $(B - I)_0 \gtrsim 2.1$ mag appear to have substantially brighter SBF magnitudes with respect to model predictions.

In addition, in the case of M32, the age and chemical composition derived from this panel do not agree with properties inferred from *I*-band SBF or literature data. Again, the SBF measured is brighter with respect to model expectations for a $t \sim 5$ Gyr, $Z \sim 0.02$ stellar system.

 $(\overline{B} - \overline{I})$ versus $(B - I)_0$.—The additional distance modulus uncertainty present in the top two panels of Figure 4 is removed in the bottom SBF color versus color panel. However, as shown in this panel, no substantial improvement occurs by using the distance-free SBF color versus integrated color with respect to the disagreement presented before.

To analyze the possible origin of the mismatch when the B-band data are considered, we have compared our SBF and color data with other sets of stellar population models (Worthey 1994; BVA01; Marín-Franch & Aparicio 2006; Fig. 5 shows the latter two sets of models). However, adopting different SBF models does not solve the mismatch in the *B* band. This is quite interesting because it can be interpreted (within the quoted small statistics and wide observational error bars) as an indication of a missing contributor to the SBF signal in the canonical B-band SSP models. A further possibility is the eventuality of a systematic bias of the *B*-band measurements, which may explain the disagreement without requiring implication of the SSP models. On the basis of extended experiments with simulations, we are led to discard the presence of systematic offsets in the *B*-band data. However, this hypothesis could not be ruled out due to the small statistics of our sample.

4.2. Comparison with Nonstandard SSP Models

A possible alternative to understand such *B*-band data/model disagreement is to consider nonstandard stellar population models. As examples of nonstandard models, we take into account two different cases: (1) SSP models with a nonstandard ratio of post-AGB to HB numbers of stars and (2) SBF models of composite stellar populations (CSPs).

1. Following the discussion concerning the contribution to SSPs of hot stars experiencing bright and fast evolutionary phases pre-



FIG. 5.—Same as Fig. 4, but for BVA01 (*top*) and Marín-Franch & Aparicio (2006; *bottom*) models. The ages in the BVA01 models range from 4 to 18 Gyr, with an increasing step of \sim 12%. The ages in the Marín-Franch & Aparicio (2006) models are 3, 5, 7, 9, 11, and 13 Gyr (stellar tracks from Bertelli et al. 1994). Chemical composition symbols are labeled at the upper right in the upper plots for both sets of models.

sented by Brocato et al. (1990, 2000) and taking into account the Worthey (1993b) comments on the effects of these stars on SBF magnitudes, in Cantiello et al. (2003) we presented a detailed analysis of the SBF magnitudes against the number of hot stars in late evolutionary phases (post-AGB). In that work it was shown that SSP models with an increased ratio of the number of post-AGB stars with respect to the number of HB stars ($N_{\text{post-AGB}}/N_{\text{HB}}$) have brighter \bar{M}_B amplitudes, while the \bar{M}_I and colors are left practically unchanged.

In Figure 6 we show the comparison of the models to the data, adopting SSP models with a $N_{\text{post-AGB}}/N_{\text{HB}}$ ratio doubled with respect to standard models. As can be recognized from the figure, all



FIG. 6.—Same as Fig. 4, but models with an increased $N_{\text{post-AGB}}/N_{\text{HB}}$ ratio (see text) are plotted.

the stellar population properties inferred from the *B*-band models agree, within the observational error bars, with the same *I*-band models described above, except for the NGC 5557 data. This means that SSP models that include a component of hot, bright stars undetectable in the SBF *I*-band models, but with a non-negligible effect on *B*-band SBF measurements, is able to reconcile the mismatch we find between standard SSP models and *B*-band measurements.

2. *B*-band SBF amplitudes may reveal the presence of populations of hot stars (extreme HB stars, post-AGB stars, young populations, metal-poor stars, etc.), even when they only represent a small fraction of the overall stellar population. B-band SBFs are therefore a valuable tool to investigate CSPs. As shown by C05, in some cases the combination of a dominant stellar population with secondary hot components of different chemical compositions and/or ages eventually allows for a better explanation of some observational properties of the galaxy. For this comparison we adopt the Blakeslee et al. (2001, hereafter BVA01) CSP models; thus, our conclusions must be considered as valid only within the limits of such a CSP scenario. The BVA01 CSP models are obtained by combining homogeneous SSP models in such a way as to mimic, at least approximately, the evolution of an elliptical galaxy. We refer the reader to the BVA01 paper for a detailed description of their composite models. In brief, SSP models are grouped into three bins according to metallicity: metal-poor (MP; 0.0004 <Z < 0.001), intermediate (INT; 0.004 < Z < 0.008), and metalrich (MR; $0.02 \le Z \le 0.03$). Then, one SSP model is randomly chosen from each metallicity bin, with some age restrictions depending on the bin. The three components are then combined according to random weighting factors (f_{MP} , f_{INT} , and f_{MR}), and fluctuation amplitudes calculated using a generalization of the Tonry & Schneider formula.

In Figure 7 the comparison of these models with observational data is presented. In the figure we mark the edges of the area covered by models. As shown in the panels of the figure, the presence of CSP eliminates the problems existing with previous standard SSP models, as all data lie within the area of the models.



Fig. 7.—SBF data compared with CSP models from BVA01. Symbols for observational data are as in Fig. 4. For the sake of clarity, only the edges of the CSP locations are shown.

By inspecting the average properties of CSP models overlapping with observational data, one concludes that

1. The galaxies at $(\bar{B} - \bar{I})_0 \sim 3.4$ and $(B - I)_0 \sim 2.2$ mag are strongly dominated by an old ($t \gtrsim 14$ Gyr) metal-rich stellar system, with a possible minor contribution due to an intermediate metallicity stellar component ($f_{\rm INT} \lesssim 20\%$) and a negligible amount of a metal-poor component ($f_{\rm MP} \lesssim 5\%$).

2. M32 data agree with CSP models composed of a comparable fraction of a metal-rich stellar system of 5–7 Gyr and an intermediate metallicity population with $t \sim 11$ Gyr.

3. NGC 5128 is the only case where the dominant component is not the metal-rich one. In this case a $t \sim 9$ Gyr, intermediatemetallicity stellar system appears to be the dominant stellar component ($f_{\rm INT} \sim 60\%$), with a secondary $t \sim 7$ Gyr metal-rich one.

4. For NGC 5322, observational data overlap with models having ~70% of the light coming from a metal-rich $t \sim 13$ Gyr component, with a substantial fraction of light coming from an intermediate-metallicity ($f_{\rm INT} \sim 20\%$) and a metal-poor ($f_{\rm MP} \sim 10\%$) component. A similar result is found for NGC 5557, with the difference being that the metallicity of the most metal-poor component in this case is $Z \sim 0.0004$.

In addition to the two previous nonstandard SSP models, we have also considered the case where an SSP is obtained using α -enhanced stellar tracks, based on the recent models by Lee et al. (2007). The use of α -enhanced SBF/color models led us to estimate chemical compositions that were on average a factor of 0.3 dex higher with respect to our previous conclusions, with substantially unchanged ages, but the aforementioned mismatch is not reconciled. Thus, we can exclude the α -enhancement as the driving source of the *B*-band mismatch, at least within the limit of the scenario presented by Lee et al. (2007).

Although the above conclusions must not be overinterpreted and considered valid only within the limits of the specific nonstandard models taken into account and the low S/N of the *B*-band SBF data, these results possibly point out that (1) *I*-band SBF magnitudes are confirmed as a powerful distance indicator, as they exhibit a small dependence on the detailed properties of the stellar population in the galaxy; (2) *B*-band SBF amplitudes are sensibly affected also by a small component of a hot stellar system (extreme HB stars, post-AGB stars, young populations, metal-poor components, etc.) and represent a valuable tool with which to study the presence of these stars and/or stellar populations in unresolved stellar systems.

5. CONCLUSIONS

In this paper we have carried out the first extensive study on *B*-band SBF measurements for distant galaxies, based on measurements obtained from ACS imaging data for a sample of six elliptical galaxies. In a previous paper (C05) we succeeded in detecting *I*-band SBF radial gradients for the same sample of objects. The quality of *B*-band images did not allow us to obtain SBF measurements in different galaxy regions. Moreover, after a few image tests, we have decided that only three of these *B*-band SBF measurements could be considered reliable.

We have added to our sample the only two other galaxies with *I*- and *B*-band SBF measurements available from the literature: M32 and NGC 5128. The analysis of the observational properties of this sample of galaxies shows that, using the standard SSP models from the SPoT group and various models from other authors, the stellar population properties derived from *I*-band SBF versus $(B - I)_0$ color data/model comparison agree with the stellar population properties known in literature derived from other indicators. In brief, the most massive objects appear to be dominated by an old ($t \ge 10$ Gyr) metal-rich, $Z \ge 0.02$ stellar component; M32 light is dominated by a $t \sim 5$ Gyr, $Z \sim 0.02$ stellar system, while NGC 5128 light seems to be dominated by a $t \sim 3$ Gyr, $Z \ge 0.01$ population.

In spite of this, we find that the *B*-band comparison of the models to the data is not satisfactory, especially for the red $[(B - I)_0 \ge 2.1]$ galaxies in our sample. In order to try to solve such a disagreement, we have presented a comparison of data with

nonstandard stellar population models. In particular, we have used prescriptions based on two different approaches.

Models with an enhanced number of hot (post-AGB) stars.— These models appear to resolve almost completely the disagreement present in the standard SSP models, within the limit of the observational uncertainty. The only galaxy whose properties do not seem to be well interpreted in this scenario is NGC 5557.

Composite stellar population models.—Within this scenario, the SBF measurements are all included in the region of the SBF color diagrams covered by the CSP models. In particular, these models show that the light of the galaxies in our sample at $(B - I)_0 \gtrsim 2.1$ mag can be interpreted as dominated by an old, $t \gtrsim 10$ Gyr, $Z \gtrsim 0.02$ stellar component, in some cases accompanied by a non-negligible amount of lower metallicity stellar components. As an example, NGC 5557 data are nicely reproduced by models including a small fraction (~10% of the total light) of old, $Z \sim 0.0004$ stars.

In conclusion, our results confirm the theoretical expectations that \overline{B} data are not well suited for distance study and, together with SBF colors such as $\overline{B} - \overline{I}$, they represent a valuable tool with which to investigate the properties of unresolved stellar systems, with particular regard to the hot stellar component. As a concluding remark, we emphasize that the use of *B*-band SBF, SBF color, and SBF radial gradient data to study the properties of the stellar systems of external galaxies relies on the availability of highquality observational data. The data used for this work are generally characterized by low-S/N ratios; based on the simulations and results presented in this paper for *B*-band SBFs, we suggest that higher S/N data (S/N $\gtrsim 10$) are required in order to carry out a detailed study of stellar population properties based on this technique.

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APPENDIX

SIMULATING "REALISTIC" CCD IMAGES OF ELLIPTICAL GALAXIES

In this appendix we outline the major steps of the procedure in order to simulate CCD images of elliptical galaxies adopted in § 3. The procedure has been properly developed to include the SBF signal in the galaxy model.

One of the basic inputs of these simulations is the R05 SSP models, which fix the chemical content and the age of the SSP for each simulation. One of the capabilities of the SPoT stellar synthesis code is to generate N_{sim} independent simulations of SSPs with fixed age and metallicity. Once the SSP total mass is fixed, the SPoT code is able to randomly populate the IMF of the stellar system. The code is implemented to reliably simulate stars on all post-MS phases: RGB, HB, AGB, etc.; see Brocato et al. (1999, 2000) and R05 for details. At fixed age, metallicity, and IMF shape, the simulations obtained have, on average, similar properties (according to the average mass of the population), but each single simulation differs from the others for statistical reasons.

We use such a capability (1) to simulate a "realistic" galaxy, which also includes the SBF signal, whose amplitude is fixed by the input properties of the SSP. Then, (2) we measure fluctuation amplitudes of the simulated galaxy, applying the procedure described in § 2.2.3. Finally, (3) the SBF measured is compared with the input one to verify if and how, in the case of low-S/N images, the measurements are affected.

First of all, we simulate a galaxy with a de Vaucouleurs (1948) $r^{1/4}$ luminosity profile, although the procedure also accepts a generic Sersic (1968) $r^{1/n}$ profile. Starting from the smooth *analytic profile* whose SBF is zero, we built a *realistic profile* to simulate the Poissonian fluctuation due to the star counts, which, as mentioned before, constitutes the physical basis of the SBF signal. To simulate the fluctuations, at each fixed radius r_* , we substitute the well-defined analytic surface brightness $\mu(r_*)_{an}$ in all N_{pix} pixels corresponding to this radius, with the surface brightness of a simulated SSP belonging to a sample of N_{pix} SSP simulations having $\langle \mu(r_*)_{SSP} \rangle = \mu(r_*)_{an}$; in this way, the brightness profile of the galaxy is preserved, and the Poissonian fluctuation due to star-count fluctuation is included.

This procedure (which is repeated at all radii) requires a large number of SSP models, according to the number or radii one wants to simulate. We note once more that since the SSP is chosen by the user, the galaxy SBF amplitude is an input parameter; for example, by using the R05 models for an SSP having Z = 0.02 and t = 14 Gyr, the input SBF is $\overline{M}_B \sim 2.9$ in the *B* band, or $\overline{M}_I \sim -1.2$ in the case of *I*-band simulations.



FIG. 8.—Power spectra of the residual frame for a galaxy simulated without (*left*) and with (*right*) the SBF pixel-to-pixel variation. The strong variations visible at $k \leq 50$ are due to the extra correlation at these scales added by the large-scale smoothing operation. In the right panel, the best fit to the data is shown as a solid line.

At this point, to simulate a fully realistic CCD image, we included the effect of the PSF, external sources (globular clusters and galaxies), and instrumental noise. To simulate the effect of the PSF on the data, the galaxy image is convolved with the PSF profile before adding the external sources (which are already convolved with the instrumental PSF). The external sources were added according to a fixed total LF of globular clusters and galaxies. This luminosity function, similar to those shown in Figure 2, is of the sum of a power law for galaxies, and a GCLF. Galaxies are randomly distributed on the galaxy image, and globular clusters were distributed using an inverse power law centered on the galaxy. A constant sky value is also added to the image. Finally, the photon and detector noises are added by using the IRAF task mknoise, according to the readout noise and gain properties of the ACS.

It must be emphasized that, in addition to the input parameters already introduced (i.e., galaxy profile index, density and spatial distribution of GCs, density of background galaxies, PSF shape, age and metallicity of the SSP), there are also some other user-defined parameters in the galaxy simulation that are not discussed here (distance, effective magnitude and effective radius, exposure time, field of view, zero-point magnitude, sky brightness, etc.). Once the simulation has been completed, the whole procedure described in § 2.2.3 (sky evaluation, galaxy modeling, source detection and masking, LF fitting, and SBF measurement) is run on the simulated CCD images.

In order to show the effect of introducing the Poissonian variation between adjacent pixels, in Figure 8 we show the power spectrum of the residual frames for an image simulated with (*right panel*) and without (*left panel*) the SBF signal. The difference clearly emerges: the spectrum of the image without the SBF is flat (i.e., no SBF signal is revealed), while the power spectrum of the image with the SBF has the characteristic PSF shape.

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