Surface Brightness Fluctuations as Stellar Population Indicators

John P. Blakeslee

Herzberg Institute of Astrophysics, National Research Council of Canada, Victoria, B.C. V9E 2E7

Abstract. Surface Brightness Fluctuations (SBF) can provide useful information about the unresolved stellar content of early-type galaxies and spiral bulges. The absolute SBF magnitude $M$ in a given passband depends on the properties of the stellar population and can be predicted by population synthesis models. SBF measurements in different bandpasses are sensitive to different evolutionary stages within the galaxy stellar population. Near-IR SBF magnitudes are sensitive to the evolution of stars within the AGB phase, especially the thermally pulsing AGB, while SBF in the blue and UV are sensitive to the hot horizontal branch and post-AGB stages. Thus, multi-band SBF studies can constrain important evolutionary parameters. Empirically, SBF data at the red end of the optical spectrum ($i$, $z$, and potentially $y$) remain excellent distance indicators. I briefly review some recent work on stellar populations using SBF, primarily from an observational point of view.

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1. INTRODUCTION: THE SBF METHOD

The surface brightness fluctuations (SBF) method measures the intrinsic pixel-to-pixel intensity variance in a galaxy image resulting from statistical fluctuations in the numbers and luminosities of the stars within individual pixels. Since the SBF signal is convolved with the point spread function, one measures the Fourier space amplitude of the power spectrum on the scale of the PSF in the galaxy-subtracted image. The ratio of SBF variance to galaxy surface brightness has units of flux and scales inversely with the square of the galaxy distance. This ratio is usually converted to a magnitude called $m$. The distance can be determined if the absolute $M$, which depends on both the photometric bandpass and the stellar population, is known from empirical or theoretical calibration. SBF measurements in multiple bands can provide useful distance-independent information on the stellar content of a galaxy.

The SBF method was first quantified by Tonry & Schneider (1988). The Cefalù stellar populations workshop where this contribution was presented marked an interesting anniversary, being twenty years to the month since the publication of that seminal work. The first major application of the SBF method was by Tonry et al. (1990) for a sample of Virgo galaxies in the $VRI$ bandpasses. They also made a first attempt to predict the behavior of $M$ as a function of galaxy color. Soon afterward, Tonry (1991) presented the first fully empirical SBF calibration, giving $M_I$ as a function of $(V−I)$. Following these
early efforts, a large ground-based SBF survey (Tonry et al. 1997, 2001) presented a redetermination of the empirical $I$-band SBF calibration and measured distances for 300 early-type galaxies and spiral bulges within about 40 Mpc. For a comprehensive review of the first decade of SBF studies, see Blakeslee, Ajhar, & Tonry (1999).

Although the major part of SBF research has been concerned with the measurement of extragalactic distances, peculiar velocities, and three-dimensional structure in the local universe, recently there has been renewed interest in SBF as a stellar population indicator. This is because SBF is sensitive to the properties of the brightest stars in a galaxy in a given bandpass, and the detailed evolution of these brightest stars is usually not well constrained, especially for old, metal-rich stellar populations. There are few if any Galactic or Magellanic star clusters where such models can be tested directly against resolved stellar systems.

There have been several recent theoretical efforts to predict SBF magnitudes for various bandpasses and stellar populations (Liu et al. 2000; Blakeslee et al. 2001; Mei et al. 2001; Cantiello et al. 2003; Mouhcine et al. 2005; Raimondo et al. 2005; Marin-Franch & Aparicio 2006; Lee et al. 2009). Cerviño et al. (2008) have recently made a rigorous study of the theoretical underpinnings of the SBF method. Optical and near-IR SBF measurements for Magellanic Cloud star clusters of varying ages also provide important tests for stellar population models (González et al. 2004; González-Lópezlira et al. 2005; Raimondo et al. 2005). Although there is broad agreement in the predictions for the most common SBF bandpasses (especially $I$ band), the agreement among different models, and between models and observations, worsens in the near-IR and UV/blue. We cannot be comprehensive in the limited space of this review, and we refer the interested reader to the original works for details. See also the contributions by M. Cantiello, R. Gonzalez-Lopezlira, and G. Raimondo in this volume. Here we simply highlight a few results from recent SBF work related to stellar population issues.

2. STELLAR POPULATION EFFECTS ON SBF MAGNITUDES

In order to work as a distance indicator, the stellar population dependence of the SBF magnitude must be well calibrated. This has worked best in the $I$ and $z$ bands, where the relation between $m$ and galaxy color has the smallest scatter (e.g., Blakeslee et al. 2001; Côté et al. 2004). We now discuss the most recent calibrations of the SBF method and the difficulties (and opportunities) in modeling the stellar population effects on SBF magnitudes at various wavelengths.

2.1 SBF as a Distance Indicator: Some Recent Work

Most of the recent work on SBF distances has focused either on dwarf galaxies in southern groups and clusters observed with large aperture ground-based telescopes (e.g., Jerjen et al. 2004; Mieske et al. 2006; Dunn & Jerjen 2006) or on early-type galaxies observed with the HST Advanced Camera for Surveys Wide Field Channel (ACS/WFC). SBF studies with ACS/WFC F814W bandpass (similar to $I$) include the first optical SBF distances out to $\sim 100$ Mpc or beyond (Biscardi et al. 2008; Blakeslee et al., in preparation), a measurement of the distance of the peculiar gas-rich lenticular
FIGURE 1. Combined SBF $z_{850}$ vs $(g_{475} - z_{850})$ color calibration for our ACS Virgo and Fornax cluster survey galaxies (from Blakeslee et al. 2009). SBF magnitudes for the Fornax galaxies are shifted brighter by the best-fit relative distance modulus of $0.42 \pm 0.03$ mag. The curve represents the best-fit cubic polynomial calibration for the dependence of $z_{850}$ on $(g_{475} - z_{850})$.

galaxy NGC 1533 in the Dorado group (Barber Degraaff et al. 2007), and studies of SBF gradients in galaxies (Cantiello et al. 2005, 2007b; discussed below).

The most extensive SBF work with the ACS to date has been in the F850LP band ($z_{850}$) as part of the ACS Virgo and Fornax cluster surveys (Côté et al. 2004; Jordán et al. 2007). Mei et al. (2005, 2007) present the SBF analysis, calibration, distance measurements for 90 early-type galaxies in the ACS Virgo survey, and Blakeslee et al. (2009) present the same for 43 galaxies in the ACS Fornax survey. The latter study also presents a recalibration based on the combined Virgo and Fornax samples.

Figure 1 shows the resulting $z_{850}$-band SBF calibration from Blakeslee et al. (2009). The dependence of $z_{850}$ on $(g_{475} - z_{850})$ is nonlinear and can be well described by a cubic polynomial. The fit yields a highly precise relative distance modulus of $0.42 \pm 0.03$ mag (including systematic uncertainties) for Fornax with respect to Virgo. The intrinsic scatter in the method is estimated empirically to be just 0.06 mag for galaxies with $(g_{475} - z_{850}) > 1$, but increases at bluer colors (the compactness of Fornax makes it possible to measure this small intrinsic scatter). Mei et al. (2005) showed that the general behavior (with a zero-point shift) of SBF in $z_{850}$ was reasonably approximated by predictions from Bruzual & Charlot (2003) simple stellar population (SSP) models of varying age and metallicity. However, it is not possible to predict the scatter in the SBF relations from SSP models. Chemo-evolutionary or semi-analytic models are required for this, although some estimates can be made from simple monte carlo simulations (Blakeslee et al. 2001). A fully successful model should predict the very tight $z_{850}$ vs $(g_{475} - z_{850})$ relation with increased scatter at the blue end.

At present, significant uncertainties remain in SBF model predictions even in well-studied bandpasses. For instance, Figure 2 compares SBF predictions in the $I$ band from Padova and Teramo/BaSTI SSP models (see Lee et al. 2009 for full details). The predictions are given both with and without the contributions from the thermally pulsing
colors to the rate of post-AGB evolution. The observational data disagreed with standard model predictions, but Cantiello et al. showed that the models could be brought into agreement with the data by adjusting the post-AGB

AGB (TP-AGB) stage. Two things are worth noting: there are large differences between the two sets of model predictions (left panel), and the highly uncertain TP-AGB stage has a very large effect (compare left and right panels). The agreement between the sets of models is better when this stage is omitted, but of course it is needed to match the observations (represented by the thick lines).

2.2 Multi-band SBF: Hot Horizontal Branches, TP-AGB, Post-AGB, etc.

Worthey (1993b) showed theoretically that SBF measurements in the UV could provide quantitative information on the presence of extended hot horizontal branch stars in elliptical galaxies and other unresolved stellar systems. According to the models used by Worthey, the presence of a hot horizontal branch could make the $U$-band SBF magnitude brighter by 3 mag in a metal-rich early-type galaxy. The effect at shorter wavelengths, such as the F284W band of HST/WFPC2, was even larger. However, the SBF signal is very faint at these wavelengths, and to date there have been no practical demonstrations of the usefulness of $U$-band SBF for this purpose. With the coming of large ground-based telescopes equipped with blue sensitive detectors (and hopefully the UVIS channel of WFC3) this may soon change.

Although the ACS/WFC has no sensitivity shortward of 4000 Å, this instrument (before its sad demise) afforded the first samples of reliable $B$-band (F435W) SBF measurements beyond the Local Group (Cantiello et al. 2007b), which have proven to have interesting implications for stellar population synthesis. Cantiello et al. (2007b) demonstrated the sensitivity of SBF $B−T$ colors to the rate of post-AGB evolution. The observational data disagreed with standard model predictions, but Cantiello et al. showed that the models could be brought into agreement with the data by adjusting the post-AGB
However, this solution was not unique, since an unmodeled hot horizontal branch or other missing components could also cause the observed discrepancy. Additional SBF measurements in the UV (to constrain further the properties of the hot component) and near-IR (sensitive to the post-AGB star progenitors) could fully resolve this issue. Multi-band optical/IR SBF data are thus relevant to such problems as AGB evolution and the UV excess in elliptical galaxies (e.g., Buzzoni & Gonzalez-Lopezlira 2008).

Blakeslee et al. (2001) found that the treatment of the AGB phase was responsible for some large discrepancies in the near-IR SBF predictions of different models; see also the discussion by Liu et al. (2000). Figure 3, adapted from Lee et al. (2009) shows a dramatic demonstration of the effects of the TP-AGB phase on near-IR SBF (in the HST F160W bandpass). For both the Padova and Teramo/BaSTI sets of models, the inclusion of the TP-AGB phase actually reverses the sense of the dependence of the SBF magnitude on color, so that the near-IR SBF brightens at bluer colors, instead of becoming fainter as it would without the TP-AGB. See Lee et al. (2009) for details.

The original expectations from models were that near-IR SBF magnitudes would brighten at redder colors (e.g., Worthey 1993a). It was a surprise when the reverse was found observationally (Jensen et al. 1998, 2003). The modeling of the AGB phase was likely much of the reason for the erroneous prediction. For the most part, the inclusion of the AGB in population synthesis relies on imperfectly constrained empirical prescriptions, rather than true evolutionary models. It is evident from the figures and comparisons with observations that nature has ordained a better behaved AGB phase than those included in the population models. The relations between SBF magnitude and integrated color are tighter than might be expected from current models.

**FIGURE 3.** Comparison of Padova and Teramo/BaSTI stellar population model SBF predictions, similar to Figure 2 but here shown for the HST NICMOS F160W band. The empirical relation from Jensen et al. (2003) is shown as a thick solid line. The importance of the TP-AGB phase is considerably greater in the near-IR. The effect of these stars in fact reverses the sense of the dependence of the SBF magnitude on color, so that the near-IR SBF brightens as observed at bluer colors, instead of becoming fainter as it would without the TP-AGB. See Lee et al. (2009) for details.
SBF data can provide powerful constraints to aid in the development of true AGB evolutionary codes for inclusion in the next generation of stellar population models.

3. SBF AND STELLAR POPULATION GRADIENTS

Until now we have discussed mean colors and SBF magnitudes, but these quantities vary within galaxies, most notably because of radial gradients in stellar population properties. SBF gradients were known from ground-based data for a few galaxies (Tonry 1991; Sodemann & Thomsen 1995, 1996; Tonry et al. 2001), but until recently there were no systematic studies. NGC 205 was the first galaxy where an SBF gradient was noted. It is unusual in that its center is blue and it becomes redder outward, the reverse of typical gradients. This is because the gradient is due to relatively recent central star formation, and therefore an age effect. The slope of the dependence of $m_I$ on $(V-I)$ is also shallower than that of the mean dependence for galaxies.

Cantiello et al. (2005, 2007a) have used the ACS/WFC to make the first studies of SBF gradients in significant samples of galaxies (see Figure 4). They show that the size of the internal SBF vs color slope for multiple annuli within a galaxy can reveal whether the gradients are due to age or metallicity. In most cases, they are metallicity gradients, but in some cases an age gradient appears equally or more important. The galaxies with age gradients tend to be bluer and show some evidence for past mergers (e.g., NGC 1344). At these optical wavelengths, age and metallicity variations cause qualitatively similar SBF vs color relations, though with different slopes. It would be extremely interesting to study internal SBF gradients in the near-IR where pure age or metallicity variations would translate to very different dependences of SBF magnitude on color. With improvements in near-IR instruments, this is now becoming possible.
4. SBF AND TOTAL STELLAR MASS: \( \overline{N} \)

The distance-independent “fluctuation count” \( \overline{N} \) is defined as \( \overline{N} = \overline{m} - \overline{m}_{\text{tot}} = +2.5 \log \left[ \frac{L_{\text{tot}}}{\overline{L}} \right] \) (Tonry et al. 2001), where \( L_{\text{tot}} \) is the galaxy total luminosity and \( \overline{L} \) is the mean “fluctuation luminosity” corresponding to magnitude \( \overline{m} \), which depends on the stellar population. The ratio \( L_{\text{tot}}/\overline{L} \) is a distance-independent galaxy luminosity in units of \( \overline{L} \) and scales with the number of stars in the galaxy (and thus with stellar mass). Figure 5 shows the correlation of \( \overline{N} \) with color from Blakeslee et al. (2009), a consequence of the mass-metallicity relation. \( \overline{N} \) also shows a good correlation with velocity dispersion \( \sigma \), tighter than even the Mg\(_2\)-\( \sigma \) relation (Blakeslee et al. 2002).

The correlation with color means that \( \overline{N} \) can also be used to calibrate SBF distances. Depending on the color baseline and properties of the data sample, the SBF calibration based on \( \overline{N} \) may show less scatter than that from color (Blakeslee et al. 2002, 2009). However, the calibration is then no longer based purely on stellar population properties, but involves a galaxy mass scaling relation. Thus, luminous blue galaxies and small red galaxies deviate from the calibration, and there may be systematic environmental effects similar to those of the fundamental plane. For these reasons, the preferred calibration uses galaxy color, but the behavior of \( \overline{N} \) itself would be interesting to examine with semi-analytic galaxy modeling.

5. OUTLOOK

Multi-band SBF studies are a unique and quite promising way of constraining stellar population properties, especially when combined with additional information. SBF data could help enormously in understanding TP-AGB evolution and hot stellar components.
in elliptical galaxies. Although there has been much theoretical modeling in this regard, the observational studies to date have been limited. The current lack of an efficient large-format space-based camera is a big blow, but currently available large-format near-IR imagers and the coming generation of multi-band digital sky surveys provide interesting prospects for new SBF studies. We have only scratched the surface of this field.

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