Stellar Populations of Elliptical Galaxies from Surface Brightness Fluctuations

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Abstract.
We are using optical/IR surface brightness fluctuations (SBFs) to validate the latest stellar population synthesis models and to understand the stellar populations of ellipticals. Integrated light and spectra measure only the first moment of the stellar luminosity function ($\Sigma n_i L_i$). Since SBFs also depend on the second moment ($\Sigma n_i L_i^2$), they provide novel information, in particular about the reddest, most luminous RGB and AGB stars, which are the most difficult stars to model. SBFs can also provide useful new constraints on the age/metallicity of unresolved stellar populations in ellipticals. Finally, developing accurate stellar population models benefits several aspects of SBF distance measurements to galaxies.

1. Introduction

When observing a nearby elliptical or bulge of a spiral galaxy, there are two distinct characteristics in the galaxy’s surface brightness. The first is the most obvious: the galaxy is brightest in the center and grows fainter with increasing radius. The second characteristic is only apparent in good seeing conditions: the surface brightness is clumpy on the scale of the seeing disk. These clumps, which can be a few percent of the mean surface brightness for the nearest galaxies like M 31 and M 32, arise from Poisson statistical fluctuations in the number of stars per seeing disk. Historically, this effect was known as “incipient resolution.” In the modern context, they are called surface brightness fluctuations (SBFs).

Tonry & Schneider (1988) devised a technique to quantify SBFs and to use them as a distance indicator for undisturbed early-type galaxies. Specifically, they proposed using the ratio of the 2nd moment of the stellar luminosity function...
Figure 1. The cumulative contribution of different stars to the K-band (2.2 µm) integrated light and SBFs for a single-burst population from Bruzual & Charlot (1998). The x-axis goes from the least evolved (main-sequence) stars on the left to the most-evolved (AGB) stars on the right using an arbitrary index. The integrated light arises from stars of all phases; about 50% comes from the RGB, but the contribution of the different RGB phases is basically degenerate. The SBFs originate only from the upper RGB and AGB, making them a powerful probe of these stars in early-type galaxies.

\( \bar{L} \equiv \frac{\sum n_i L_i^2}{\sum n_i L_i} \) (1)

where \( n_i \) is the number of stars of type \( i \) with a luminosity of \( L_i \). \( \bar{L} \) has units of luminosity and is expressed in astronomer’s units as \( \bar{M} \) and \( \bar{m} \), the absolute and apparent SBF magnitude, respectively.

2. Utility for Stellar Population Studies

Since \( \bar{M} \) is an intrinsic property of the LF, SBFs can be useful for studying the stellar populations of early-type galaxies. The potential parameter space to explore is very large, since the “age” and “metallicity” of the stars can be a complex combination of formation epoch and subsequent history (e.g., Kaufmann, in this volume). SBFs provide data unique from the integrated light/spectra of these galaxies. Because of their \( L^2 \) dependence, SBFs are very sensitive probes of the most luminous stars, the cool red giant stars (Figure 1). Modeling these stars’ interior structure and emergent spectra is very challenging. Also, since bright RGB and AGB stars evolve quickly, only a handful of each are present in any star cluster in the Milky Way or Magellanic Clouds. Therefore, SBF mea-
Measurements, which arise from the stellar population of entire galaxies, provide one of the best observational tests of our current understanding of these stars.

3. Models versus SBF Data

Recent observational and theoretical advances make now a ripe time to revisit and expand SBF stellar population studies. Past modeling (Tonry et al. 1990; Buzzoni 1993; Worthey 1993) used the previous generation of evolutionary tracks (VandenBerg or Revised Yale Isochrones) based on older stellar opacities. The optical SBF dataset has been expanded and improved considerably (Tonry et al. 1997), and a growing body of IR data has widened the spectral coverage.

Figure 2 presents $K$-band SBF data for Fornax cluster ellipticals from Liu et al. (1999b) and Jensen et al. (1998). Fornax is appealing since it is close enough to have a Cepheid distance measured with HST (Silbermann et al. 1999) and is compact on the sky, implying the galaxies basically lie at the same distance. Predictions from Bruzual & Charlot (1998) single-burst models are overplotted; these use Padova evolutionary tracks, stellar spectra of Lejeune et al. (1997), and a semi-empirical AGB prescription (Charlot & Bruzual 1991). (See Bruzual, in this volume.) The good agreement between data and models means the lifetimes, luminosities, and colors of the bright RGB and AGB stars are roughly correct, or else multiple errors are cancelling each other out (e.g., Charlot et al. 1996).

The BC98 models agree worse with the $I$-band empirical SBF calibration (Tonry et al. 1997) than with the $K$-band data, which has lead us to revise the most evolved stars in the models (Liu et al. 1999a). This illustrates the usefulness of SBF tests. Although the models agree reasonably well with integrated colors
of elliptical galaxies and Local Group globular clusters, it is the SBF comparison which reveals possible weaknesses in the modeling of the most luminous stars.

4. New Tools for Breaking the Age/Metallicity Degeneracy

In old populations, \( M \) is expected to be very metal-dependent, since it strongly tracks the RGB and AGB, whose colors are governed by metallicity (Frogel et al. 1983). Therefore, SBF data are potentially very useful in characterizing the stellar content of ellipticals. Broad-band colors are degenerate in age and metallicity, with changes of \( d(\log \text{age})/d(\log Z) \approx 3/2 \) preserving the color (Worthey 1994 [W94]; Worthey, this volume). Absorption line indices can be more age- or metal-sensitive, e.g., \( H\beta \) and \( H\gamma \) are age-sensitive (\( \lesssim 1.0 \)) and \( \text{Mg}_2 \) and \( \text{C}_2\lambda 6731 \) are metal-sensitive (\( \approx 2 - 5 \)). In comparison, IR SBF magnitudes are predicted by the BC98 and W94 models to have \( d(\log \text{age})/d(\log Z) \gtrsim 6 \) in old populations. This suggests IR SBF data combined with Balmer absorption indices could effectively disentangle age and metallicity effects in ellipticals.

5. SBF Distances: Building a Better Standard Candle

Developing accurate models is critical for measuring distances to galaxies from SBFs. Optical/IR SBF distances can be measured to \( cz \approx 10^4 \) km/s and therefore to obtain \( H_0 \), but accurate distances rely on accurate \( K \)-corrections to account for the redshifting of the galaxy spectrum. Moreover, models can guide us to better observations. For instance, \( I \)-band SBF distances use the \((V-I_C)\) integrated galaxy color to account for stellar population variations from galaxy to galaxy (Tonry et al. 1997). Both the BC98 and W94 models suggest that \((V-K)\) or \((I-K)\) colors, which are more metallicity-driven, would lead to a better correction, reducing the scatter by \( \gtrsim 50\% \). The wider spectral ranges of these colors also lead to greater tolerance of errors in photometry or reddening than \((V-I_C)\). Finally, accurate models could provide a purely theoretical calibration for SBF distances, independent of any Cepheid calibration.

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