# On the Fundamental Line of Globular Clusters Systems

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## Overview

This poster presents some results published in Pasquato & Bertin (2008) and other results from some work currently in progress. We address the issue of the existence of a Globular Cluster (GC) Fundamental Plane (FP) in the ($\log R_e$, $\log\sigma$, $SB_e$) parameter space (see Djorgovski 1995) by model-independently analyzing surface brightness profiles, distance moduli and velocity dispersions of a sample of $48$ galactic GCs. We study selection effects with non-parametric statistical tests. We find a FP which is compatible with that of early-type galaxies, but with higher scatter. The deviations from the plane correlate with the central slope of the surface brightness profile (from Noyola & Gebhardt 2006). We find evidence for bimodality in the distribution of the quantity $\log K_V/(M/L)$ (log virial coefficient over mean mass-to-light ratio) by use of kernel density estimation methods. The galactic GC system then appears to be composed of at least two dynamically different populations. Both results are suggestive of the presence of intermediate-mass black-holes in a subsample of GCs.

We find that in the ($\log R_e$, $\log\sigma$, $SB_e$) space our sample occupies a rather slim, axisymmetric region. The relevant scaling relation is then around a line, rather than a plane, confirming a result noted earlier (see Bellazzini 1998). This lies at the origin of the difficulties in the fit by a plane often mentioned in previous investigations. Such a Fundamental Line relation would imply a pure photometric scaling law relating luminosity to the effective radius which we test on a larger sample of $156$ galactic and extra-galactic GCs. We find that such a relationship exists and that there is a trend of the residuals to it with GC age, but we are yet unable to confirm that this dependence is due to dynamical evolution.

## The FP of GCs

On a sample of $48$ galactic GCs with measured line-of-sight velocity dispersions (from Pryor & Meylan 1993), well determined horizontal-branch distance moduli (from Ferraro et al. 1999, Recio-Blanco et al. 2005) and apparent magnitudes and half-light radii obtained from model-independent spline smoothing of Trager et al. (1995) surface-brightness profiles, we find a FP of the form:

$$\log R_e = (1.09 \pm 0.31)\log\sigma + (0.30 \pm 0.05)SB_e - (5.52 \pm 2.35)\ , \qquad (1)$$

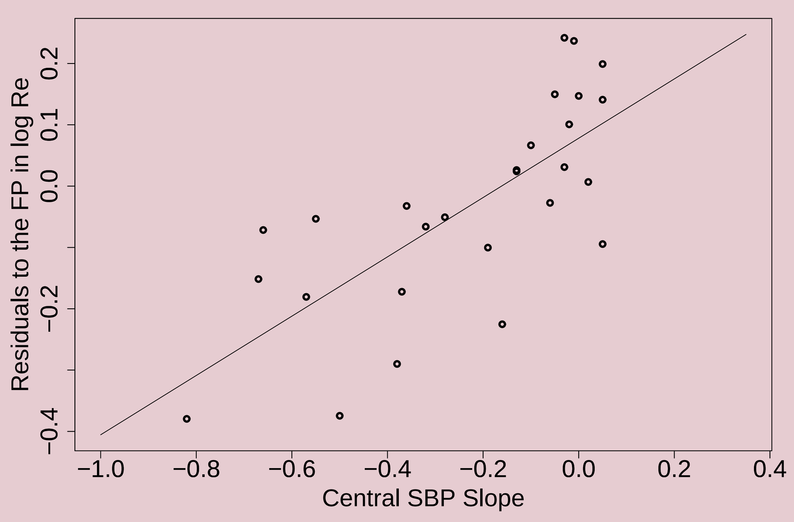
which is compatible with previous results (Djorgovski 1995) and with the FP of early-type galaxies (Jørgensen et al. 1996):

$$\log R_e = 1.24\log\sigma_0 + 0.33 SB_e - 5.895\ , \qquad (2)$$

also in the zero point, where $R_e$ is measured in pc.

## A fourth parameter

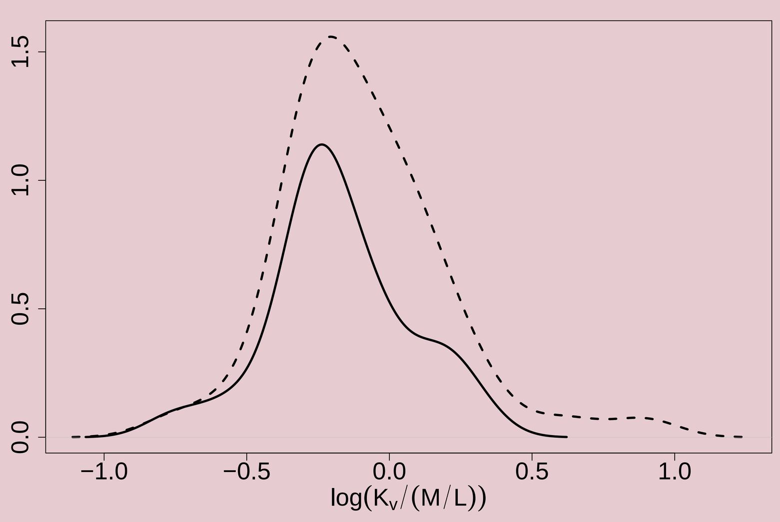
We find a $\chi^2 = 9.56$ for the FP relationship, suggesting that the scatter is not due to observational errors alone. Our sample includes GCs that have a power-law cusp-like behavior of the surface brightness profile in the central region. We find that the logarithmic slope of such profile at the center, as measured by Noyola & Gebhardt (2006), correlates with our FP residuals with a correlation coefficient of $0.73$. The cuspiness of the inner surface-brightness profile of GCs may be related to core collapse or to the presence of an intermediate-mass black-hole.




Correlation of the FP residuals in $\log R_e$ with the logarithmic slope of the central surface brightness profile (from Pasquato & Bertin 2008)

## The structure of the $\log K_V/(M/L)$ distribution

We have reconstructed the distribution of $\log K_V/(M/L) \equiv GL/(R_e\sigma^2)$ (see Bertin et al. 2002) for our sample, by means of kernel density estimation techniques. The $K_V/(M/L)$ distribution looks bimodal, even if we choose a slightly larger bandwidth than optimal so to err on the side of oversmoothing. The indication of bimodality is stronger if the analysis is restricted to the $28$ systems for which the line-of-sight velocity dispersion is obtained from central, integrated light measurements, while for the entire sample of $48$ GCs it almost disappears. Such a bimodality does not reflect the subdivision of galactic GCs in disk and halo clusters, because metallicity does not correlate with $\log K_V/(M/L)$. On the other hand, intermediate mass black holes might play a role, by their influence on the central velocity dispersion.




Distribution of $\log K_V/(M/L)$ for GCs with central velocity dispersions measured in integrated light (solid line) and for the entire sample (dashed line). Units were set by imposing $K_V/(M/L) = 1$ for NGC $104$. From Pasquato & Bertin (2008).

## From the FP to the Fundamental Line

Djorgovski (1995), when first fitting the GC FP via least squares, noticed an instability of the fit related to the choice of the dependent variable and suggested using $SB_e$, which gives "better and more stable" results. We show that one obtains significantly different FPs if $\log R_e$ or $\log\sigma$ are used instead. Interestingly, such different FPs intersect in the vicinity of a common line. We find a remarkably high degree of axisymmetry of the data-set around such a line, which explains the FP fit instability.

Such a Fundamental Line was first proposed by Bellazzini (1998), based on principal component analysis in the GC parameter space. He shows that, in such space, outer GCs (with distance to the galactic center larger than $8$ kpc) have a dimensionality which is unambiguously one.

We project the GC Fundamental Line onto the ($\log R_e$, $SB_e$) plane to predict a purely photometric scaling law approximately of the following form

$$\log R_e \propto \frac{1}{10} SB_e \qquad (3)$$

Such a projected relationship can be studied without the need for spectroscopy, so we are able to extend our study to a sample of $156$ galactic and extragalactic GCs to address the following questions:

- Do GCs follow a global luminosity vs radius scaling law compatible with the FL projection?
- How do the scatter and slope of such relationship depend on environment, GC age, and dynamical evolution?
- Ultimately, are GC scaling laws primordial or rather the effect of evolution?

## Studying the Fundamental Line in the photometric plane: the data

- We use the surface brightness profiles of Trager et al. (1995) for galactic GCs and the compilation of surface brightness profiles at the basis of McLaughlin et al. (2005) for extragalactic clusters
- Through a model-independent spline-smoothing algorithm we calculate projected half-light radius and mean surface brightness within the half-light radius for $193$ Milky Way, LMC, SMC, and Fornax clusters
- Horizontal-branch distances and reddenings from Ferraro et al. (1999) and Recio-Blanco et al. (2005) were used were available for galactic GCs; McLaughlin et al. (2005) distance estimates were adopted for extragalactic GCs
- The final selected sample contains $156$ GCs with surface brightness and quality distance data.

We make use of further data from the literature to study the evolution of the Fundamental Line with GC age and dynamical evolution:

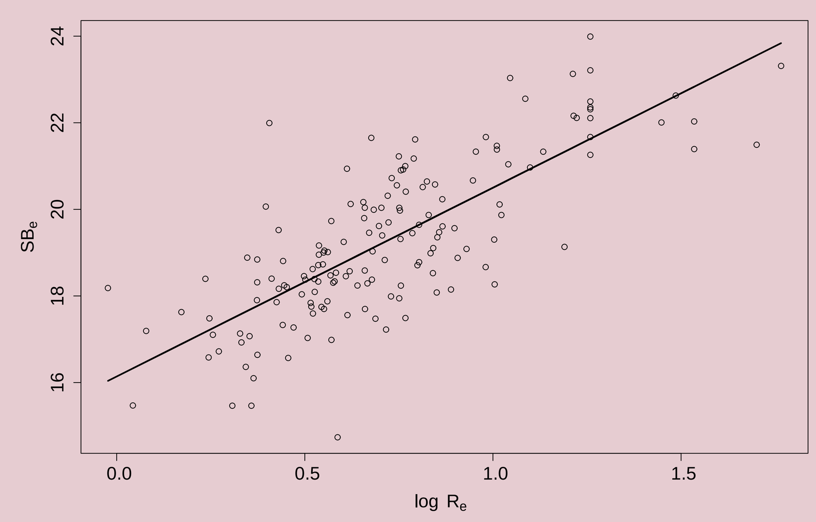
- We adopt the McLaughlin et al. (2005) ages $\tau_a$ and half-light relaxation times $\tau_r$ for extragalactic GCs
- We assign absolute ages to galactic GCs based on the De Angeli et al. (2005) relative ages by setting the log age in years of NGC $5824$ to $10.11$
- We make use of bulge and disk destruction timescales ($\tau_b$ and $\tau_d$) from Dinescu et al. (1999)

## Results and prospects

We obtain the following relationship via robust biweight fitting, over the sample of $156$ GCs:

$$\mathbf{SB}_e = (16.14 \pm 0.67) + (4.36 \pm 0.29)\log R_e \qquad (4)$$

where $\log R_e$ is measured in pc. The scatter is about $1.1$ mag with respect to $\mathbf{SB}_e$.




This differs significantly from the prediction obtained in Eq. (3) by projecting the Fundamental Line. Pasquato & Bertin (2008) found non-negligible selection effects in metallicity and concentration on their sample, which may justify this difference. Moreover, the results obtained by projecting the Fundamental Line on the photometric plane are not necessarily bound to be equal to those obtained by fitting a linear relationship directly on such plane.

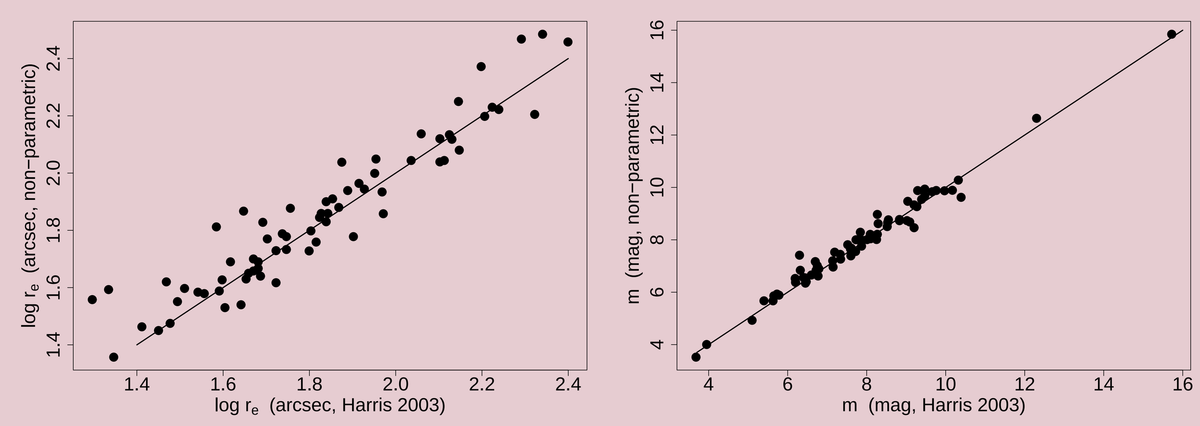
We find a trend of the fit residuals with GC age. In particular, the best linear predictor for age $\tau_a$ is:

$$\log\tau_a = -(2.57 \pm 2.43) + (0.33 \pm 0.08)\mathbf{SB}_e - (2.40 \pm 0.46)\log R_e \qquad (5)$$

So far, by binning in $\tau_a/\tau_r$ we find no significant differences in the distribution of projected Fundamental Line residuals according to a Kolmogorov-Smirnov test. The same applies to $\tau_a/\tau_d$ and to $\tau_a/\tau_b$. If this result is confirmed, the picture in which the Fundamental Line is primordial and its scatter grows over time due to dynamical evolution would be ruled out.

We plan to track the evolution of a sample of GCs on the ($\log R_e$, $\mathbf{SB}_e$) plane making use of simple semi-analytic prescriptions (e.g. Vesperini & Heggie 1997) to check how a Fundamental Line configuration evolves in time.

Given the general interest in model-independent investigations, we plan to complete a catalogue of GC fraction-of-light radii and magnitudes obtained with our spline-smoothing method.




Comparison of our model-independent half-light radii and magnitudes with the Harris (1996; catalogue updated in 2003) quantities

## Conclusions

Our model-independent approach confirms the existence of a FP of galactic GCs independent of the assumption that such clusters are well described by King models. The large error bars on the FP coefficients prevent strong conclusions as to whether the FP of GCs is indeed a continuation of that of early-type galaxies. The scatter around the FP is probably not due to observational errors only and correlates with a fourth parameter, namely the slope of the surface brightness profile at the GC center (as defined and measured by Noyola & Gebhardt 2006). The shape of the distribution of $K_V/(M/L)$ appears to be bimodal, which points against the naive interpretation that the FP of GCs just reflects the virial constraint. Both features may be related to the possible presence of intermediate mass black holes in GCs.

The difficulties in choosing an optimal variable for fitting the FP are explained by the clustering of GCs about a Fundamental Line in the ($\log R_e$, $\log\sigma$, $SB_e$) parameter space. The data-set we analyzed shows a strong axisymmetry around such a line. The Fundamental Line relation implies the existence of a pure photometric scaling law, which we study on a sample of $156$ galactic and extragalactic GCs. We find a somewhat different linear relationship between $\log R_e$ and $SB_e$ than expected based on the projection of the Fundamental Line. The residuals to such a relationship correlate with GC age, but we are yet unable to confirm that this dependence is due to dynamical evolution, either internal or mediated by the galactic environment.

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