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IMPLICATIONS OF THE KINEMATICS ON THE CHEMICAL AND DYNAMICAL PROPERTIES OF NEARBY ELLIPTICAL GALAXIES

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Abstract. We have selected 1450 elliptical galaxies from approximately 7000 galaxies presented in the Nearby Optical Galaxy sample, which is a complete, distance-limited (cz $\leq$ 6000 km/s) and magnitude-limited (B $\leq$ 14) catalog of nearby galaxies. By cross-matching this sample with SDSS database (DR10), we have found spectroscopical confirmation of 179 ellipticals with signal-to-noise ratio between 10 and 80, sufficient for calculation of full kinematical profiles of these galaxies. Also, we have calculated the Lick indices, including corrections due to the kinematics. Finally, we discuss the influence of the full line-of-sight velocity distribution on the mass estimates.

1. INTRODUCTION

The most general description of the line-of-sight velocity distribution of stars in a galaxy can be obtained using Gauss-Hermite series (van der Marel & Franx 1993, hereafter vdMF). Deriving theoretical line profiles for the outher parts of elliptical galaxies, vdMF showed that even modest velocity dispersion anisotropy when ignored yields systematic errors in both the mean radial velocity and velocity dispersion of 10% or more. This naturally influences the virial mass estimates, which correlates with σ^2, not to mention the black hole mass scaling relation ($\sim \sigma^4$), making precise calculation of velocity dispersion even more important.

In this paper, we will show that even medium resolution spectra of elliptical galaxies with very low signal-to-noise ratio (hereafter SNR) are useful for these purposes when a reliable stellar library is available. This issue is ignored in the Sloan Digital Sky Survey (hereafter SDSS) releases, for the reasons of the modest instrumental resolution ($\approx$ 70 km/s) and an assumption that the stellar kinematics has Gaussian shape. The former can be overcome by the usage of the complete as possible stellar library and the latter is close to the real picture, but deviations from Gaussian distribution, when properly taken into account, may lead to serious under/over estimation of galaxy masses.

The outline of the paper is as follows. In Chapter 2, we will present the sample of galaxies used in this paper, followed by the description of the method chosen for calculation of the full kinematical profile of galaxies in Chapter 3, along with comparison with existing work on the subject. Corrections of the measured Lick indices are presented in detail in Chapter 4.

2. DATA SAMPLE

We have selected early-type galaxies from the *Nearby Optical Galaxy catalog* (Giuricin et al. 2000) with spectral confirmation in SDSS DR10. Cross-match is performed using spatial information of galaxies as provided by the NED (*NASA/IPAC Extragalactic Database*)[1]. In the initial query we had 1450 elliptical galaxies, but were left with only 179 galaxies having spectal information. Our final sample has a median SNR of 50, from as low as 10 to 80 at the highest.

However, this was enough to obtain reliable estimates of even higher moments of the Gauss-Hermite series (h_3 and h_4), as will be described in Chapter 3. The limit was imposed by the instrumental resolution, making dispersions below this limit highly suspicious.

3. STELLAR KINEMATICS

Galaxy spectra may be regarded as a superposition of stellar spectra broadened due to the net motion of stars and redshifted. So, the observed spectrum is well described by the convolution of a stellar spectrum with the line-of-sight velocity distribution function modeled in the most general case as a Gauss-Hermite series (vdMF). However, absorption spectra resulting from stellar motions are often contaminated with emission lines produced by different mechanisms, such as recombination followed by cascade (most prominent in Balmer series) and collisional excitation followed by radiative deexcitation (responsible for the forbidden lines). Emission lines may be either masked during the determination of stellar kinematics or fitted along with some Gaussian templates having the ratio of different lines fixed (e.g. all Balmer lines will have the same disperison). The former case was used for measuring stellar kinematics, and the latter case was adopted for the Lick indices calculations for which one can clean up the spectrum easily by subtracting the best fitted emission pattern, leaving only absorbtion lines present.

We used Penalized Pixel-Fitting code (hereafter `pPXF`) presented in detail in Cappellari & Emsellem 2004, that makes fitting in the pixels space on the logarithmically rebinned spectra in order to make the redshift linear. All stellar spectra are degraded to spectral resolution of the galaxy spectrum and logarithmically rebinned. The linear combination of these spectra, having amplitudes as free parameters (i.e. weights) is broadened with Hermite polynomials normalized as in Appendix A of vdMF. The final form of the broadening function used in this paper is:

$$L(w) = \frac{1}{\sqrt{2\pi\sigma^2}} \exp(-1/2w^2) \left[\frac{h_3}{\sqrt{6}}(2\sqrt{2}w^3 - 3\sqrt{2}w) + \frac{h_4}{\sqrt{24}}(4w^4 - 12w^2 + 3) \right], \quad (1)$$

where $w = (v - V)/\sigma$ (V being radial velocity and σ velocity dispersion) and $h_3,\ h_4$ are the Hermite coefficients characterizing asymmetric and symmetric deviations from the pure Gaussian, respectively. To quantify departures of the line profile from its best fitting Gaussian, vdMF found the relation between rms deviation (D) and Hermite coefficients:

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[1] http://ned.ipac.caltech.edu/ngi/

$$D = \sqrt{\sum_{j=3}^{N} h_j^2}. \tag{2}$$

Cappellari & Emsellem 2004 used this parameter to control the robustness while introducing additional parameters to Gaussian distribution defining penalized χ_p^2 as:

$$\chi_p^2 = \chi^2(1 + \lambda^2 D^2), \tag{3}$$

where $\lambda = (0, 1)$ is the so-called bias parameter, that one must determine for the problem in question since it depends naturally on the length of the stellar template used (number of points in the fit), but also on the SNR. We have used empirical Elodie stellar library of about 1000 stars of all spectral types in the spectral range of 3900 - 6800 $\mathring{A}$ with the observational resolution of 12 km/s for the reasons given in the Lalovic (2010).

To determine the bias parameter, we have chosen one star to mimic galaxy spectrum, convolved it with a Gaussian having Full Width Half Maximum[2] (hereafter FWHM) equal to the square root of the quadratic difference between stellar and galaxy resolution $S(x)$. Then, the spectrum is broadened with the function of the form Eq. 1 with $h_3 = 0.1$ and $h_4 = -0.1$ and velocity dispersion varying from the lowest 15 km/s to as high as 400 km/s ($GH(x)$). This spectrum is divided to the desired SNR to mimic the noise. And finally, the artificial galaxy spectrum can be written as:

$$G(x) = S(x) * GH(x; w, h_3, h_4) + S(x) * GH(x; w, h_3, h_4)/SNR. \times \mathrm{RNG} \tag{4}$$

Here, RNG is a function that generates pseudorandom numbers from a normal distribution with a mean of zero and a standard deviation of one (the random number generator). For a SNR=(5,80) with a step equal to 5, we have tried to recover Hermite parameters ($h_3 = 0.1$ and $h_4 = -0.1$), using `pPXF` and also varying bias parameter from 0.0 to 1.0 for the whole range of velocity dispersions and for each SNR. The largest bias parameter for which the reconstruction was successfull was chosen for the given SNR. In this way, we come up with the formula

$$\lambda = 0.007 \times S/N + 0.068. \tag{5}$$

To deal with errors properly, we created asymptotes as the 2nd polynomial fit to the limiting points output by Monte Carlo simulations inside 3-σ sliding median excluding points bellow the SDSS resolution. The addopted error is given as the spread of the points between the asymptotes at the position of the velocity dispersion calculated in the real case of the galaxy.

We have tested our results against SDSS and Hyperleda databases to find the overall agreement (Fig. 2, left). For the purpose of comparison we have used pure Gaussian functions, since higher moments were not calculated by the SDSS pipeline. The difference is quite small (Fig. 2, right), but it certainly affects virial mass[3] (Fig. 3, left) and black hole mass[4] (Fig. 3, right) estimates.

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[2] The width of the Gaussian function at the half of its maximum value.

[3] The virial mass inside virial radius R is proportional to $2R\sigma^2/G$.

[4] See Ferrarese & Merritt (2000) for a relation between black hole mass and velocity dispersion

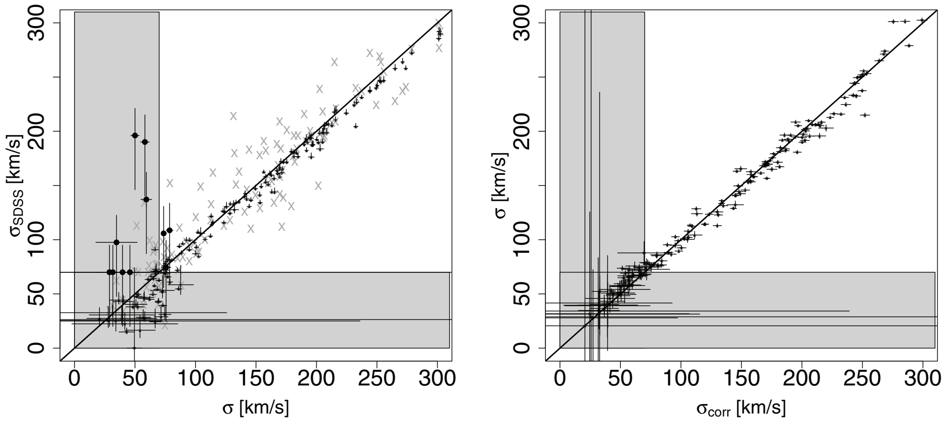

Figure 1: Left: Comparison of the calculated velocity dispersions to the SDSS pipeline values. Large points correspond to the values flagged by the SDSS and so should be considered unreliable. Overplotted are the values from Hyperleda database as gray crosses. Right: Comparison of the corrected and uncorrected values of velocity dispersion for the case h_4 parameter has nonzero values: $\sigma_{corr} = \sigma(1 + \sqrt{6}h_4)$. On both panels shaded areas lie bellow the SDSS instrumental resolution.

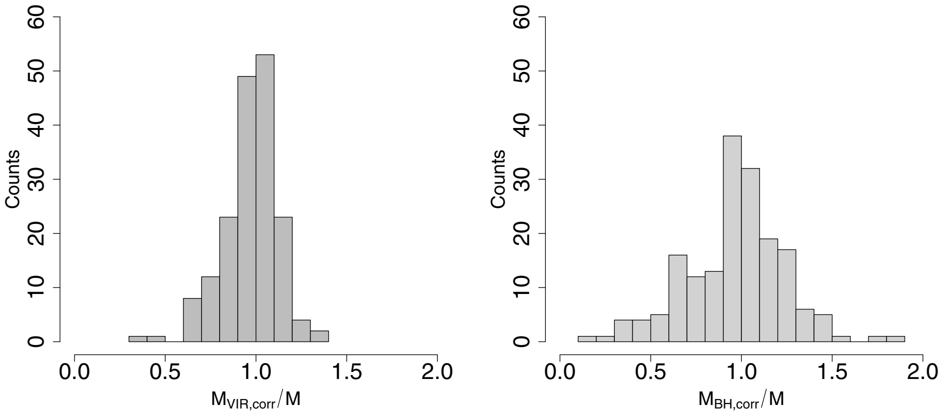

Figure 2: Left: Histogram of the virial mass estimates compared to the case where the line-of-sight velocity distribution is assumed to have Gaussian shape (scaled as σ^2). Right: The same as in the left panel, but for the black hole mass estimate $\sim \sigma^4$.

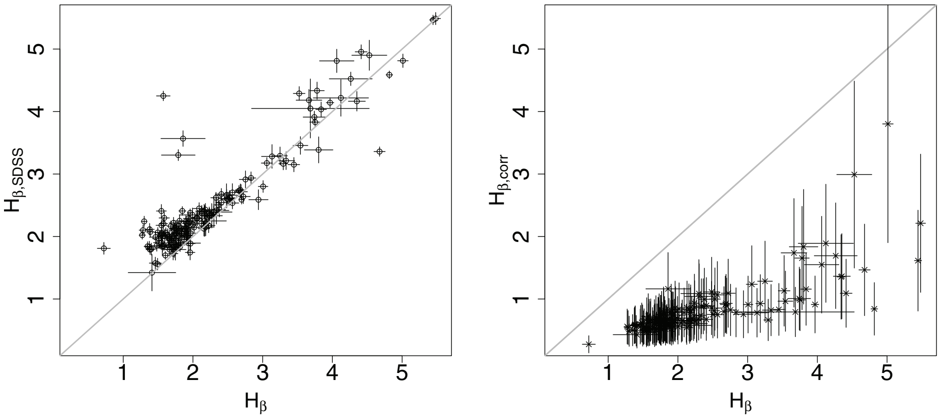

Figure 3: Left: Comparison of H_β index to SDSS pipeline values, where emission line masking and subtraction are used. Right: Corrected vs. uncorrected values of H_β index for the impact of stellar kinematics.

4. LICK INDICES

The study of galaxy properties as composite stellar systems using absorption spectral lines led to the creation of the Lick/IDS system (Faber et al. 1985; Worthey et al. 1994; Worthey & Ottaviani 1997). This system defines the standard 25 absorption line indices, that are actually equivalent widths chosen in such a way to be prominent and free of emission lines as possible[5]. Absorption line strenghts are expressed in term of indices centered on the absorption feature of interest (*index bandpass*). To the blue and red side of the index bandpass are *blue* and *red continua* determining the end points of the continuum by the simple average. Joining these two (average) points with a straight line defines *pseudocontinuum* against which the index is calculated by the area encompassed by the line itself and pseudocontinuum. These indices were measured on a large sample of stars, globular clusters and early-type galaxies for the purpose of studying their stellar populations.

To address this issue properly, it is necessary to exclude the contribution from emission lines, but also to correct for the effect of the stellar kinematics broadening. We have adopted the approach based on two publically avaliable codes: Cappellari & Emsellem's (2004) pixel fitting method and Sarzi et al's (2006) `gandalf` code. The idea is to extract stellar kinematic using `pPXF` while masking emission lines, and then to clean up the spectrum from the nebular emission using `gandalf`. `Gandalf` starts from the information on the LOSVD provided by the `pPXF` to broaden the optimal stellar template and then models emission lines with Gaussian functions to obtain the best nebular emission template. Finally, this emission template is subtracted from the galaxy spectrum to leave pure absorption line spectrum sutable for deriving the strength of stellar absorption-line features. Prior to this, galaxy spectrum is corrected for Galactic extinction using the E(B-V) value provided by NED.

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[5] http://astro.wsu.edu/worthey/html/index.table.html

For the calculation of the the Lick indices, we have used method presented in Cardiel et al. (1998) including the treatment of errors. In short, first we have degraded galaxy spectrum to Lick resolution and measured indices on both the optimal stellar spectrum before ($LS_{optimal}$) and after broadening (LS_{model}) to yield the ratio. The correction for this effect is simply:

$$LS_{corr} = LS \times \frac{LS_{optimal}}{LS_{model}} \tag{6}$$

where LS_{corr} is the corrected index and LS index measured on the emission-free galaxy spectrum (see Oh et al. 2011 for details).

We have compared our values to those provided by the SDSS and find satisfying agreement (Fig. 3, left), bearing in mind that their pipeline used other stellar library resulting in a bit different correction factor. It is clear form Fig. 3 (right) that uncorrected indices are higly overestimated and this effect must not be neglected. Also, all the values in Fig. 3 (both left and right) are corrected for the nebular emission which is reflected in their strictly positive values.

Acknowledgments

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