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MEASUREMENT OF THE LICK INDICES IN EARLY-TYPE GALAXIES: LINE-OF-SIGHT VELOCITY DISTRIBUTION CORRECTIONS FOR IC 1459

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SUMMARY: In this paper we analyse the measurements of the absorption line-strength Lick indices in the early-type galaxy IC 1459. We use the long-slit spectra of the elliptical galaxy IC 1459 from which its kinematics had previously been extracted to calculate the Lick indices for the observed spectral region (Mg_2, Fe5270, Fe5335 and H_β). We apply the usual procedure and correct the indices to the Lick spectral resolution and for the zero velocity dispersion. The procedure applied in this paper also corrects to non-Gaussian line-of-sight velocity distribution (LOSVD) observed in this galaxy, especially in its outer parts. The findings of Kuntschner (2004) were tested and it is shown that the departures from the Gaussian LOSVD may indeed cause erroneous determinations of the Lick indices. The impact of the introduction of non-Gaussian LOSVD differs for different indices. For the galaxy IC 1459 it is shown that the iron indices are especially sensitive when the correction due to anistropies is introduced: the corrections for Fe5270 and Fe5335 are ~ 10 and ~ 19 percent larger, respectively, than the corrections obtained in case of a pure Gaussian. The corrections for Mg_2 index are shown to be negligible and the corrections of the H_β index due to anisotropies are also small (below ~ 4 per cent at most).

Key words. Line: profiles – Methods: data analysis – Galaxies: elliptical and lenticular, cD – Galaxies: kinematics and dynamics – Galaxies: individual (IC 1459)

1. INTRODUCTION

In 1972 S. Faber and her collaborators started a long-term spectroscopic project that was aimed at the study of stellar populations in globular clusters and early-type galaxies. For this purpose the `Image Dissector Scanner (IDS)` on the Shane 3m telescope of Lick Observatory was used. Faber and collaborators observed a large number of galaxies, and stars of all types, field and cluster giants, subgiants and dwarfs in the spectral range from ~ 4000 Å to ~ 6200 Å with a ~ 8.6 Å FWHM resolution. The Lick group defined and measured spectral indices to monitor the strength of spectral features in stars and galaxies (see Faber et al. 1985). Note, however, that since the early papers of the Lick group the wavelength accuracy has improved and new definitions are now valid. All the calculations presented below were based on the updated version of the indices table taken from the WWW site of G. Worthey.[1]

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

Table 1: Definitions of indices calculated in this paper

Name	Index band [Å]		blue continuum [Å]		red continuum [Å]		Units
H_β	4847.875	4876.625	4827.875	4847.875	4876.625	4891.625	ang
Mg_2	5154.125	5196.625	4895.125	4957.625	5301.125	5366.125	mag
Fe5270	5245.650	5285.650	5233.150	5248.150	5285.650	5318.150	ang
Fe5335	5312.125	5352.125	5304.625	5315.875	5353.375	5363.375	ang

NOTE: Units: "mag" refers to the index measured in magnitudes, and "ang" refers to the index measured in Angstroems.

In order to define an index one should define a central band of width Δ_0 and two side bands. The "side-band level" I_s is defined to be the mean intensity over the two side bands, and the intensity of the central feature I_c is the mean intensity in the central band. There are two groups of indices: one is measured as an equivalent width (for example, iron indices):

$$w = \left(1 - \frac{I_c}{I_s}\right)\Delta_0$$

and the other is measured in magnitudes (for example Mg_2):

$$w = -2.5\,\log\left(1 - \frac{I_c}{I_s}\right).$$

The spectra that we used were centered at ~5150 Å to be near the Mg_2 feature and the range was ~ 700 Å. The indices we have measured are given in Table 1 (for a full list of definitions the reader is referred to the WWW site of G. Worthey).

This paper addresses the measurements of the Lick indices. For the application and modeling of these quantities the reader is referred to abundant literature (see e.g. Trager et al. 2000a,b, Thomas, Maraston and Bender 2003). The plan of the paper is as follows: in Section 2 we present the kinematics of IC 1459, because it is of crucial importance for the task of this work; in Section 3 we explain our measurement procedure and introduce the corrections which we apply; in Section 4 we present our results and, finally, in Section 5 we discuss the obtained results and draw the conclusions.

2. KINEMATICS OF IC 1459

IC 1459 is a giant E3 elliptical galaxy. It covers 5.2×3.8 arcmin on the sky (RC3). Its heliocentric radial velocity is 1663 ± 74 km s^{-1} (taken from the LEDA database) which means that, using the Hubble constant equal to 70 km s^{-1} Mpc^{-1}, one arcsec in this galaxy corresponds to ~ 117.16 pc. The effective radius of IC 1459 is 33″ (= 3.87 kpc). The absolute blue magnitude of IC 1459 is −20.52. This galaxy has some peculiar features: a fast counterrotating stellar core (Franx and Illingworth 1988), twisted isophotes (Williams and Schwarzschild 1979), dust lanes and patches near the nucleus (Sparks et al. 1986) and an ionized gaseous disk at the core that rotates along the major axis in the same direction as the majority of stars in the galaxy (opposite to that of the stellar core) (Forbes et al. 1995).

IC 1459 was observed by J. Danziger on August 28-30 1997 using the ESO NTT and EMMI in the Red Medium Spectroscopy mode. The major photometric axis of this galaxy was observed and integrated stellar long-slit spectra were taken. The observational details are given in Samurović and Danziger (2005) and we here only briefly remind the reader that the data reduction was performed in the `MIDAS`[2] environment and the extraction of kinematics was done using "Gauss-Hermite Fourier Fitting software" (described in van der Marel and Franx 1993).

Before we present the observational results we briefly explain the meaning of the measured kinematical parameters. First, we introduce the function which describes line-of-sight velocity distribution (LOSVD, also called velocity profile, VP). This function defines the fraction of the stars that contribute to the spectrum which have LOS velocities between $v_{\rm LOS}$ and $v_{\rm LOS} + dv_{\rm LOS}$ and is given as $F(v_{\rm LOS})dv_{\rm LOS}$. If one assumes that all stars have identical spectra $S(u)$ (where u is the spectral velocity in the galaxy spectrum), then the intensity that is received from a star with LOS velocity $v_{\rm LOS}$ is $S(u - v_{\rm LOS})$. Summing over all stars one gets:

$$G(u) \propto \int dv_{\rm LOS} F(v_{\rm LOS}) S(u - v_{\rm LOS}), \qquad (1)$$

where $G(u)$ is the galactic spectrum. Up to 1993, a purely Gaussian form of the LOSVD was used. However, van der Marel and Franx (1993) and Gerhard (1993) showed that the LOSVD can be modeled more accurately as a truncated Gauss-Hermite ($F_{\rm TGH}$) series consisting of a Gaussian multiplied by a polynomial:

$$F_{\rm TGH}(v_{\rm LOS}) = \Gamma \frac{\alpha(w)}{\sigma}\left[1 + \sum_{k=3}^{n} h_k H_k(w)\right]. \qquad (2)$$

Here Γ represents the line strength, $w \equiv (v_{\rm LOS} - \bar{v})/\sigma$, $\alpha \equiv \frac{1}{\sqrt{2\pi}} \exp(-w^2/2)$, where $\bar{v}$ and σ are free

[2] `MIDAS` is developed and maintained by the European Southern Observatory (`http://www.eso.org/esomidas/`).

Table 2: Stellar kinematics of IC 1459. We show velocity, velocity dispersion and the Gauss-Hermite parameters h_3 and h_4 with their observational errors.

r	v [km s^{-1}]	Δv	σ [km s^{-1}]	$\Delta\sigma$	h_3	Δh_3	h_4	Δh_4
0.00	0.000	13.584	335.607	13.451	0.059	0.028	0.021	0.035
0.56	-37.990	13.910	336.161	13.939	0.048	0.029	0.006	0.034
1.12	-37.794	12.155	335.259	11.845	0.052	0.025	0.018	0.031
1.68	-64.612	11.498	335.384	10.854	0.056	0.024	0.027	0.030
2.24	-75.225	10.723	329.267	10.165	0.070	0.024	0.021	0.028
2.80	-73.989	10.187	323.050	9.706	0.077	0.023	0.015	0.027
3.36	-73.019	11.881	329.219	11.498	0.074	0.025	0.022	0.031
3.92	-66.862	11.266	322.989	10.751	0.074	0.025	0.025	0.030
4.48	-60.989	11.259	324.849	10.803	0.060	0.025	0.007	0.029
5.04	-41.327	11.824	330.300	11.608	0.042	0.024	0.019	0.030
5.60	-38.528	12.040	329.954	11.596	0.049	0.026	0.022	0.031
6.16	-24.357	11.714	326.543	11.177	0.043	0.024	0.031	0.031
6.72	-29.812	11.613	318.630	11.122	0.031	0.026	0.025	0.031
7.28	-30.432	10.741	318.308	9.805	0.017	0.024	0.045	0.031
7.84	-19.168	11.165	318.031	11.215	0.033	0.024	-0.004	0.029
8.40	-23.930	11.973	315.753	11.706	-0.001	0.027	0.015	0.033
8.96	-30.108	10.450	317.690	9.865	0.014	0.024	0.022	0.030
9.52	-6.441	11.508	307.354	10.749	0.010	0.026	0.017	0.033
10.08	-6.510	11.344	314.264	10.728	0.004	0.025	0.032	0.032
10.64	-2.948	12.971	305.709	11.974	0.006	0.031	0.034	0.038
11.20	-5.864	13.393	313.513	12.989	0.013	0.031	0.005	0.037
11.76	8.645	12.140	317.611	11.560	-0.002	0.026	0.021	0.034
12.32	1.161	13.877	310.264	14.580	-0.001	0.031	-0.019	0.030
12.88	11.280	14.275	306.889	13.395	-0.003	0.032	0.016	0.041
13.44	15.194	11.843	296.120	11.235	-0.006	0.030	0.024	0.036
14.00	11.109	12.372	304.950	12.266	0.019	0.040	0.009	0.036
15.12	11.135	16.895	308.245	13.638	0.005	0.033	0.035	0.040
15.68	-1.714	13.908	306.853	12.062	-0.015	0.027	-0.017	0.030
16.51	8.970	12.161	299.174	10.874	0.007	0.027	0.021	0.032
17.63	20.065	11.180	292.456	10.608	-0.013	0.028	0.031	0.034
18.75	23.074	10.995	293.284	11.272	-0.007	0.031	0.040	0.037
19.87	23.781	12.012	296.985	9.357	-0.015	0.026	0.073	0.032
20.99	23.446	10.453	294.350	11.685	-0.036	0.033	0.048	0.039
22.11	24.334	12.491	285.037	11.656	-0.026	0.034	0.044	0.040
23.23	34.540	11.958	286.098	11.885	-0.023	0.034	0.058	0.041
24.36	55.632	12.820	290.625	13.682	-0.046	0.037	0.033	0.045
25.75	42.642	14.619	286.444	12.825	-0.013	0.034	0.013	0.041
27.43	49.239	12.670	281.305	12.066	-0.025	0.035	0.046	0.042
29.11	55.822	13.102	283.043	10.983	-0.026	0.034	0.041	0.040
30.79	35.901	12.108	283.977	11.879	-0.047	0.036	0.054	0.043
32.74	51.540	12.847	268.418	10.091	-0.020	0.033	0.052	0.038
34.98	48.461	10.967	273.178	12.674	-0.021	0.038	0.025	0.044
37.22	64.489	13.359	275.997	12.821	-0.011	0.039	0.070	0.048
39.73	62.445	14.594	257.978	14.135	-0.041	0.041	0.021	0.048
42.81	100.226	13.232	238.817	12.458	-0.044	0.046	0.058	0.051
46.16	82.138	13.676	248.227	13.837	-0.034	0.046	0.038	0.054
49.79	66.456	15.757	243.430	12.874	-0.065	0.050	0.083	0.054
53.96	75.908	13.897	221.309	13.329	-0.116	0.049	0.126	0.054
58.97	86.800	14.635	216.606	15.407	-0.088	0.058	0.121	0.063
65.33	121.000	16.481	183.567	22.703	-0.199	0.094	0.239	0.094
75.79	92.493	17.883	149.142	16.297	-0.043	0.106	0.382	0.107
89.61	102.160	19.720	144.155	24.391	-0.024	0.133	0.266	0.133

parameters; h_k are constant coefficients and $H_k(w)$ is a Gauss-Hermite function, that is a polynomial of order k. We truncate the series at $k = 4$ thus taking into account the h_3 and h_4 parameters. With these expressions, the LOSVD can be calculated by varying the values of $\bar{v}$, σ, h_3 and h_4 until the convolution of the function $F_{\rm TGH}(v_{\rm LOS})$ with a template star spectrum best reproduces the observed galaxy spectrum. The optimal fit is obtained using a nonlinear least-squares fitting algorithm. If the form of the LOSVD is close to the Gaussian form, then $\bar{v}$ and σ will be approximately equal to $\bar{v}_{\rm LOS}$ and $\sigma_{\rm LOS}$. Parameters h_3 and h_4 are important because they measure asymmetric and symmetric departures from the Gaussian, respectively. If one detects a positive (negative) value of the h_3 parameter, that would mean that the distribution is skewed towards higher (lower) velocities with respect to the systemic velocity. On the other hand, if one detects $h_4 > 0$, this means that the distribution is more peaked than the Gaussian at small velocities with more extended high-velocity tails (the radial orbits dominate); for $h_4 < 0$ the distribution is more flat-topped than the Gaussian (the tangential orbits dominate).

In Table 2 and Fig. 1 we present the kinematical profile for the major axis of IC 1459 because it is of importance for the discussion that follows. Note that we assume symmetry about the y-axis and, therefore, we folded all the observational data (velocity, velocity dispersion and the Gauss-Hermite parameters, h_3 and h_4), taking into account that velocity and h_3 parameter are odd functions while velocity dispersion and h_4 are even functions of the radius. The aforementioned fast counterrotating stellar core is clearly visible in the innermost regions of IC 1459 (top panel).

The galaxy IC 1459 is a very interesting case because it shows departures from the Gaussian beyond $\sim 1R_e$ with rather large values of the h_4 parameter, which suggests radial orbits in the outermost regions. The purpose of the present study is to quantify the influence of the observed anisotropies in the stellar motion on the measured Lick indices.

3. MEASUREMENTS OF THE LICK INDICES

We measured the line strength indices using the procedures we have written in `FORTRAN` which we embedded in the `MIDAS` scripts. We relied on the `AVINT` routine by Davis and Rabinowitz (1984) that was included in the SLATEC library of programs[3]. This routine, based on overlapping parabolas, calculates the integral

$$\int_a^b f(x)dx \qquad (3)$$

when $f(x)$ is tabulated in nonequally spaced abscissas – this is the most general case: in our calculations abscissas were equally spaced. To verify the results, we tested the routine using some elementary functions and also some standard spectra obtained from the site of G. Worthey, and the agreement was excellent with the elementary functions and very good in the case of the Worthey's spectra. The obtained results confirmed that our procedure is suitable for the extraction of the Lick indices from the long-slit spectra.

The routines we have written were used on the deredshifted spectra, and the measurements were standardized to a Lick system. Two usual steps

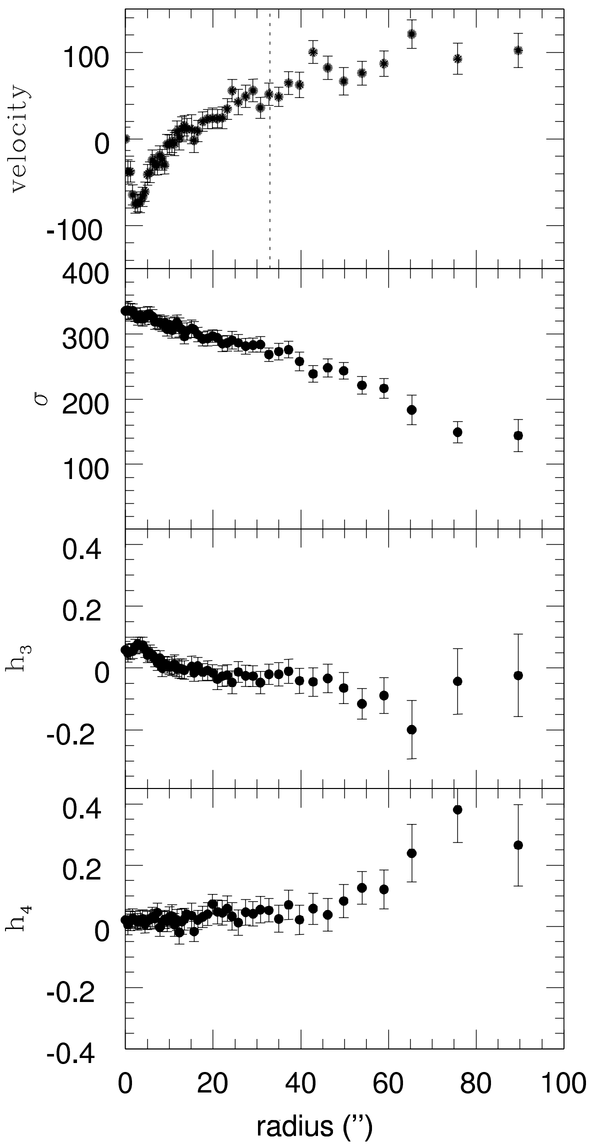

Fig. 1. *Stellar kinematics of IC 1459 for the major axis. From top to bottom: velocity, velocity dispersion, h_3 and h_4 parameters. One effective radius is marked in the top panel by a vertical dashed line.*

[3]`http://www.netlib.org/slatec/src`

necessary to transform the spectra into the Lick system (see for example Fisher, Franx and Illingworth 1995, Gonzales 1993, Halliday 1998) are:

- correction to the Lick IDS spectral resolution (∼ 8.2Å at ∼ 5200 Å) and
- correction to zero velocity dispersion.

Kuntschner (2004) suggested that the Lick indices are sensitive to the LOSVD corrections to non-Gaussian LOSVDs, and assumed that LOSVD can be described by the Gauss-Hermite series decribed above. He then calculated the corrections of the indices due to anisotropies, assuming given *fixed* values of the h_3 and h_4 parameters (he took: $|h_3| \leq 0.2$ and $|h_4| \leq 0.2$ taking into account all possible combinations but presented results only for $|h_3|$ and $|h_4|$ which vary out to 0.1). The following question however remains: How to calculate the Lick indices when we encounter different (i.e. not tabulated by Kunschner (2004)) values of the h_3 and h_4 parameters? This is the case of IC 1459 for which we have measured these paramaters out to $\sim 3R_e$ and we see in Table 1 that different combinations of parameters are possible; we also note that the $|h_4|$ parameter may take *much higher* values than 0.1 presented by Kuntschner; see his Figs. 7 and 8. This is the reason for which we decided to write a procedure which calculates the corrections of different Lick indices assuming different values of velocity dispersion and Gauss-Hermite h_3 and h_4 parameters. The procedure is written in the `IDL`[4] programming language and its algorithm is described below. Therefore, we list here the third correction to be applied in order to measure the Lick indices:

- correction to non-Gaussian LOSVD.

The first correction is related to the different spectral resolution of our observations and those of the Lick `IDS`. The spectra of the Helium-Argon calibration lamp were inspected to measure the instrumental resolution and then the galaxy frame was broadened so as to match the Lick spectral resolution (∼ 8.2 Å at ∼ 5200 Å).

The second correction for the effects of the velocity dispersion included the following steps: the spectra of the template star (the star HR2701 was observed with the same observational setup in the same nights as the galaxy IC 1459) were broadened for a given velocity dispersion at a given position (for example at 0.″56 the stellar spectrum was broadened with $\sigma = 336.161$ km s^{-1} which is the maximal velocity dispersion encountered in this galaxy) always assuming *a pure Gaussian* function (i.e. $h_3 = h_4 \equiv 0.0$).

Following the paper of Carollo, Danziger and Buson (1993), the estimate of the errors (given in Table 3 and Fig. 2) for the indices (I) was calculated using:

$$\epsilon_i = \frac{\sqrt{\mathrm{OBJ} + 2 \times \mathrm{DK} + \left(1 + \frac{1}{N_{\mathrm{rows}}}\right) \times \mathrm{SKY} + \mathrm{ron}^2}}{\mathrm{OBJ}}, \quad (4)$$

where OBJ is the total count in the object, SKY is the total count in the sky, DK is the total count in dark, and ron is the read-out noise of the CCD. The term $\frac{1}{N_{\mathrm{rows}}}$ comes from the subtraction of a sky averaged on N_{rows}(=30) rows from the galactic spectra. One can now define the error on the line-strength index:

$$\Delta I = \mathrm{coeff} \times \sqrt{\sum_{i=c_1,c_2,b} \epsilon_i^2},$$

where c_1, c_2 and b indicate respectively the two continua and the index band. The coefficient is equal to $1.08(= -2.5\log\ e)$ for the Mg_2 index and to $\frac{(C_{\mathrm{feat}} \times W_{\mathrm{pix}})}{C_{\mathrm{cont}}}$ for the atomic indices (Fe5270, often abbreviated to Fe1; Fe5335, often abbreviated to Fe2; and H_β); C_{feat} is the total count in the feature, W_{pix} is the pixel width in Å, and C_{cont} is the average continuum.

Then a correction factor (which we call $C^0(\sigma)$ in the following because being taken for the pure Gaussian function) is calculated by comparing each broadened spectrum with a measurement for the original unbroadened stellar spectrum. In the case of the molecular index Mg_2, the correction factor is defined as a difference between the measurement of the original unbroadened stellar spectrum and that of the spectrum broadened to a particular velocity dispersion:

$$C^0(\sigma) = I_{\mathrm{orig}} - I^0(\sigma). \quad (5)$$

For the atomic indices, the correction factor is defined as the ratio between the original and the smoothed (with a pure Gaussian) line indices:

$$C^0(\sigma) = I_{\mathrm{orig}}/I^0(\sigma). \quad (6)$$

Here (and also below when we deal with a modified Gaussian) "I" stands for index and the original unbroadened index is denoted with "orig". Since the bands are wide, the corrections for Mg_2 are very small. On the contrary, the corrections for the iron indices and H_β can be significant. When the corrections are taken into account and applied to a galactic spectrum, we obtain the values of different indices given in Table 4 and Fig. 2 (open circles).

Finally, the third correction is due to non-Gaussian LOSVD observed in the galaxy IC 1459. To apply the aforementioned `IDL` routine it is necessary to have the full kinematical profile of a given galaxy (velocity dispersion, and the Gauss-Hermite parameters h_3 and h_4). The procedure is analogous to that applied in the case when we assume a pure Gaussian function, but with the inclusion of the measured non-zero values of the Gauss-Hermite h_3 and h_4 parameters. This, for example, means that at the last measured point of IC 1459 we broaden the template star spectrum by $\sigma = 144.155$ km s^{-1}, $h_3 = -0.024$ and $h_4 = 0.266$ and calculate the correction in an analogous way as earlier but instead of Eqs. (5) and (6) we now use for the molecular Mg_2 index:

[4] `http://www.ittvis.com/ProductServices/IDL.aspx`

Table 3: Lick indices of IC 1459 corrected for Lick resolution and velocity dispersion assuming a pure Gaussian function. For each index, the observational errors are also given.

r	$Mg_2{}^0$	$\Delta Mg_2{}^0$	$Fe5270^0$	$\Delta Fe5270^0$	$Fe5335^0$	$\Delta Fe5335^0$	$H_\beta{}^0$	$\Delta H_\beta{}^0$
0.00	0.370	± 0.002	4.126	± 0.003	3.241	± 0.007	0.341	± 0.003
0.56	0.369	0.002	4.129	0.003	3.227	0.007	0.351	0.004
1.12	0.369	0.002	4.100	0.003	3.246	0.007	0.345	0.004
1.68	0.369	0.002	4.097	0.003	3.242	0.007	0.360	0.004
2.24	0.368	0.002	4.058	0.003	3.198	0.007	0.362	0.004
2.80	0.369	0.002	4.042	0.003	3.135	0.007	0.378	0.004
3.36	0.368	0.002	4.060	0.003	3.196	0.007	0.385	0.004
3.92	0.367	0.002	4.041	0.003	3.134	0.007	0.405	0.004
4.48	0.367	0.002	4.050	0.003	3.170	0.008	0.417	0.004
5.04	0.368	0.002	4.091	0.003	3.208	0.008	0.443	0.004
5.60	0.366	0.002	4.059	0.003	3.224	0.008	0.459	0.004
6.16	0.367	0.002	4.051	0.003	3.176	0.008	0.486	0.004
6.72	0.365	0.002	4.017	0.003	3.129	0.008	0.504	0.004
7.28	0.366	0.002	4.016	0.003	3.122	0.008	0.535	0.004
7.84	0.364	0.003	4.011	0.003	3.146	0.009	0.559	0.004
8.40	0.364	0.003	4.013	0.003	3.106	0.009	0.593	0.004
8.96	0.364	0.003	4.000	0.003	3.142	0.009	0.618	0.005
9.52	0.363	0.003	3.959	0.003	3.045	0.009	0.648	0.005
10.08	0.361	0.003	3.972	0.004	3.130	0.010	0.681	0.005
10.64	0.360	0.003	3.958	0.004	3.078	0.010	0.710	0.005
11.20	0.359	0.003	3.987	0.004	3.152	0.010	0.743	0.005
11.76	0.359	0.003	3.987	0.004	3.177	0.011	0.777	0.005
12.32	0.356	0.003	3.950	0.004	3.156	0.011	0.807	0.005
12.88	0.355	0.003	3.923	0.004	3.096	0.011	0.835	0.006
13.44	0.352	0.003	3.856	0.004	3.053	0.012	0.862	0.006
14.00	0.352	0.004	3.908	0.004	3.126	0.012	0.897	0.006
15.12	0.351	0.004	3.929	0.005	3.134	0.012	0.928	0.006
15.68	0.347	0.004	3.913	0.005	3.149	0.013	0.988	0.007
16.51	0.346	0.004	3.900	0.005	3.140	0.014	1.003	0.007
17.63	0.342	0.004	3.847	0.005	3.100	0.015	1.061	0.007
18.75	0.340	0.004	3.838	0.006	3.113	0.015	1.108	0.008
19.87	0.338	0.005	3.854	0.006	3.142	0.016	1.149	0.008
20.99	0.331	0.005	3.865	0.006	3.091	0.018	1.213	0.009
22.11	0.330	0.005	3.829	0.007	3.000	0.018	1.242	0.009
23.23	0.328	0.006	3.826	0.007	3.000	0.019	1.267	0.009
24.36	0.325	0.006	3.844	0.007	2.989	0.020	1.285	0.010
25.75	0.323	0.006	3.810	0.008	2.959	0.021	1.304	0.010
27.43	0.320	0.006	3.796	0.008	2.877	0.022	1.323	0.011
29.11	0.316	0.007	3.771	0.008	2.828	0.023	1.340	0.011
30.79	0.311	0.007	3.747	0.009	2.806	0.024	1.358	0.012
32.74	0.306	0.007	3.623	0.009	2.640	0.025	1.370	0.012
34.98	0.304	0.008	3.681	0.010	2.747	0.026	1.393	0.013
37.22	0.299	0.008	3.515	0.010	2.580	0.028	1.426	0.014
39.73	0.298	0.008	3.380	0.011	2.417	0.030	1.436	0.014
42.81	0.298	0.009	3.231	0.011	2.256	0.031	1.450	0.015
46.16	0.299	0.010	3.220	0.012	2.282	0.034	1.497	0.016
49.79	0.299	0.010	3.217	0.013	2.297	0.036	1.491	0.017
53.96	0.301	0.011	3.224	0.014	2.268	0.038	1.426	0.018
58.97	0.303	0.011	3.348	0.015	2.338	0.040	1.335	0.019
65.33	0.300	0.013	3.250	0.016	2.198	0.044	1.303	0.021
75.79	0.290	0.014	3.067	0.018	1.959	0.049	1.446	0.024
89.61	0.273	0.016	2.940	0.021	1.888	0.057	1.271	0.028

Table 4: Lick indices of IC 1459 corrected for Lick resolution and velocity dispersion taking into account non-zero Gauss-Hermite parameters. For each index, the observational errors are also given.

r	$\mathrm{Mg_2}^{GH}$	$\Delta\mathrm{Mg_2}^{GH}$	$\mathrm{Fe5270}^{GH}$	$\Delta\mathrm{Fe5270}^{GH}$	$\mathrm{Fe5335}^{GH}$	$\Delta\mathrm{Fe5335}^{GH}$	$\mathrm{H_\beta}^{GH}$	$\Delta\mathrm{H_\beta}^{GH}$
0.00	0.370	± 0.002	4.146	± 0.003	3.344	± 0.007	0.351	± 0.003
0.56	0.369	0.002	4.125	0.003	3.281	0.007	0.357	0.004
1.12	0.369	0.002	4.116	0.003	3.333	0.007	0.353	0.004
1.68	0.369	0.002	4.128	0.003	3.357	0.007	0.371	0.004
2.24	0.368	0.002	4.074	0.003	3.304	0.007	0.373	0.004
2.80	0.368	0.002	4.045	0.003	3.221	0.007	0.388	0.004
3.36	0.368	0.002	4.078	0.003	3.307	0.007	0.398	0.004
3.92	0.367	0.002	4.063	0.003	3.246	0.007	0.418	0.004
4.48	0.367	0.002	4.044	0.003	3.228	0.008	0.425	0.004
5.04	0.368	0.002	4.113	0.003	3.289	0.008	0.453	0.004
5.60	0.366	0.002	4.083	0.003	3.318	0.008	0.471	0.004
6.16	0.367	0.002	4.093	0.003	3.287	0.008	0.499	0.004
6.72	0.366	0.002	4.051	0.003	3.213	0.008	0.514	0.004
7.28	0.366	0.002	4.089	0.003	3.252	0.008	0.550	0.004
7.84	0.364	0.003	3.995	0.003	3.154	0.009	0.563	0.004
8.40	0.364	0.003	4.039	0.003	3.145	0.009	0.597	0.004
8.96	0.364	0.003	4.035	0.003	3.208	0.009	0.627	0.005
9.52	0.363	0.003	3.985	0.003	3.093	0.009	0.655	0.005
10.08	0.362	0.003	4.026	0.004	3.217	0.010	0.692	0.005
10.64	0.360	0.003	4.014	0.004	3.172	0.010	0.722	0.005
11.20	0.359	0.003	3.992	0.004	3.172	0.010	0.747	0.005
11.76	0.359	0.003	4.024	0.004	3.232	0.011	0.785	0.005
12.32	0.356	0.003	3.918	0.004	3.104	0.011	0.800	0.005
12.88	0.355	0.003	3.950	0.004	3.137	0.011	0.840	0.006
13.44	0.352	0.003	3.896	0.004	3.114	0.012	0.869	0.006
14.00	0.352	0.004	3.918	0.004	3.158	0.012	0.904	0.006
15.12	0.351	0.004	3.986	0.005	3.231	0.012	0.945	0.006
15.68	0.347	0.004	3.888	0.005	3.098	0.013	0.977	0.007
16.51	0.346	0.004	3.932	0.005	3.199	0.014	1.014	0.007
17.63	0.343	0.004	3.899	0.005	3.180	0.015	1.071	0.007
18.75	0.341	0.004	3.903	0.006	3.220	0.015	1.124	0.008
19.87	0.339	0.005	3.973	0.006	3.339	0.016	1.180	0.008
20.99	0.332	0.005	3.950	0.006	3.208	0.018	1.227	0.009
22.11	0.331	0.005	3.902	0.007	3.109	0.018	1.255	0.009
23.23	0.328	0.006	3.921	0.007	3.148	0.019	1.288	0.009
24.36	0.326	0.006	3.906	0.007	3.062	0.020	1.289	0.010
25.75	0.323	0.006	3.833	0.008	2.989	0.021	1.307	0.010
27.43	0.320	0.006	3.871	0.008	2.988	0.022	1.338	0.011
29.11	0.316	0.007	3.839	0.008	2.924	0.023	1.352	0.011
30.79	0.312	0.007	3.830	0.009	2.930	0.024	1.377	0.012
32.74	0.306	0.007	3.702	0.009	2.759	0.025	1.385	0.012
34.98	0.304	0.008	3.642	0.010	2.683	0.026	1.382	0.013
37.22	0.300	0.008	3.616	0.010	2.738	0.028	1.454	0.014
39.73	0.298	0.008	3.413	0.011	2.460	0.030	1.434	0.014
42.81	0.298	0.009	3.309	0.011	2.370	0.031	1.453	0.015
46.16	0.299	0.010	3.272	0.012	2.357	0.034	1.499	0.016
49.79	0.300	0.010	3.328	0.013	2.464	0.036	1.497	0.017
53.96	0.301	0.011	3.389	0.014	2.519	0.038	1.423	0.018
58.97	0.304	0.011	3.509	0.015	2.580	0.040	1.335	0.019
65.33	0.300	0.013	3.530	0.016	2.608	0.044	1.295	0.021
75.79	0.290	0.014	3.377	0.018	2.340	0.049	1.498	0.024
89.61	0.273	0.016	3.145	0.021	2.130	0.057	1.307	0.028

Table 5: Corrections of the Lick indices of IC 1459. Note that in this table "Fe1" and "Fe2" were used for Fe5270 and Fe5335 indices for brevity, respectively. The superscript "0" is written when a pure Gaussian is used, and the superscript "GH" is used when the corrections due to non-zero values of the Gauss-Hermite parameters were taken into account. See text for details.

r	$C(Mg_2)^0$	$C(Fe1)^0$	$C(Fe2)^0$	$C(H_\beta^0)$	$C(Mg_2)^{GH}$	$C(Fe1)^{GH}$	$C(Fe2)^{GH}$	$C(H_\beta^{GH})$
0.00	0.0025	1.3527	1.7519	1.1148	0.0026	1.3592	1.8074	1.1465
0.56	0.0026	1.3533	1.7502	1.1186	0.0026	1.3519	1.7791	1.1367
1.12	0.0031	1.3443	1.7535	1.1126	0.0031	1.3495	1.8009	1.1402
1.68	0.0028	1.3431	1.7573	1.1135	0.0030	1.3536	1.8197	1.1485
2.24	0.0024	1.3304	1.7269	1.1160	0.0025	1.3357	1.7840	1.1501
2.80	0.0025	1.3252	1.6981	1.1073	0.0024	1.3263	1.7451	1.1378
3.36	0.0024	1.3317	1.7246	1.1168	0.0024	1.3374	1.7845	1.1527
3.92	0.0024	1.3254	1.6957	1.1074	0.0025	1.3326	1.7563	1.1432
4.48	0.0024	1.3287	1.7080	1.1117	0.0022	1.3268	1.7391	1.1327
5.04	0.0027	1.3426	1.7330	1.1101	0.0028	1.3498	1.7768	1.1346
5.60	0.0023	1.3326	1.7343	1.1111	0.0024	1.3403	1.7847	1.1395
6.16	0.0027	1.3305	1.7122	1.1061	0.0030	1.3443	1.7721	1.1377
6.72	0.0024	1.3199	1.6794	1.1042	0.0026	1.3313	1.7245	1.1271
7.28	0.0025	1.3196	1.6787	1.1039	0.0030	1.3436	1.7485	1.1344
7.84	0.0023	1.3195	1.6835	1.1056	0.0021	1.3141	1.6878	1.1121
8.40	0.0025	1.3204	1.6639	1.1057	0.0027	1.3290	1.6847	1.1139
8.96	0.0025	1.3181	1.6748	1.1061	0.0027	1.3294	1.7102	1.1224
9.52	0.0026	1.3047	1.6238	1.0988	0.0027	1.3134	1.6498	1.1100
10.08	0.0025	1.3110	1.6612	1.1053	0.0029	1.3286	1.7077	1.1240
10.64	0.0020	1.3068	1.6329	1.0998	0.0023	1.3250	1.6825	1.1183
11.20	0.0024	1.3185	1.6641	1.1029	0.0024	1.3201	1.6748	1.1089
11.76	0.0026	1.3190	1.6758	1.1062	0.0028	1.3311	1.7049	1.1177
12.32	0.0023	1.3088	1.6566	1.1031	0.0021	1.2982	1.6296	1.0928
12.88	0.0020	1.2998	1.6227	1.0996	0.0022	1.3089	1.6442	1.1071
13.44	0.0012	1.2798	1.5916	1.0906	0.0015	1.2929	1.6238	1.1000
14.00	0.0017	1.2974	1.6264	1.1014	0.0017	1.3008	1.6432	1.1105
15.12	0.0021	1.3068	1.6237	1.0975	0.0025	1.3257	1.6739	1.1168
15.68	0.0020	1.3029	1.6226	1.0995	0.0019	1.2946	1.5959	1.0871
16.51	0.0015	1.2986	1.6125	1.0930	0.0017	1.3094	1.6432	1.1044
17.63	0.0015	1.2820	1.5839	1.0988	0.0018	1.2993	1.6250	1.1091
18.75	0.0022	1.2789	1.5856	1.0956	0.0026	1.3005	1.6403	1.1114
19.87	0.0029	1.2838	1.5980	1.0920	0.0037	1.3236	1.6983	1.1212
20.99	0.0014	1.2854	1.5819	1.0896	0.0020	1.3135	1.6418	1.1026
22.11	0.0022	1.2721	1.5422	1.0873	0.0026	1.2964	1.5987	1.0986
23.23	0.0018	1.2707	1.5529	1.0868	0.0024	1.3022	1.6293	1.1045
24.36	0.0022	1.2771	1.5598	1.0840	0.0027	1.2976	1.5982	1.0877
25.75	0.0022	1.2670	1.5588	1.0861	0.0023	1.2746	1.5749	1.0886
27.43	0.0026	1.2674	1.5318	1.0848	0.0030	1.2926	1.5913	1.0965
29.11	0.0020	1.2673	1.5369	1.0874	0.0024	1.2901	1.5893	1.0972
30.79	0.0022	1.2702	1.5424	1.0848	0.0027	1.2984	1.6109	1.1001
32.74	0.0020	1.2471	1.4824	1.0763	0.0023	1.2743	1.5492	1.0879
34.98	0.0023	1.2842	1.5733	1.0898	0.0021	1.2707	1.5369	1.0811
37.22	0.0022	1.2568	1.5139	1.0839	0.0027	1.2927	1.6070	1.1052
39.73	0.0018	1.2318	1.4501	1.0735	0.0020	1.2438	1.4760	1.0715
42.81	0.0017	1.2030	1.3849	1.0659	0.0019	1.2320	1.4548	1.0685
46.16	0.0015	1.2163	1.4138	1.0698	0.0017	1.2360	1.4605	1.0718
49.79	0.0013	1.2094	1.4030	1.0694	0.0017	1.2511	1.5055	1.0740
53.96	0.0016	1.1800	1.3311	1.0563	0.0018	1.2404	1.4785	1.0538
58.97	0.0014	1.1746	1.3202	1.0539	0.0016	1.2311	1.4570	1.0539
65.33	0.0012	1.1307	1.2321	1.0401	0.0013	1.2283	1.4622	1.0333
75.79	0.0006	1.0913	1.1572	1.0203	0.0013	1.2017	1.3821	1.0573
89.61	0.0006	1.0858	1.1464	1.0181	0.0012	1.1612	1.2932	1.0472

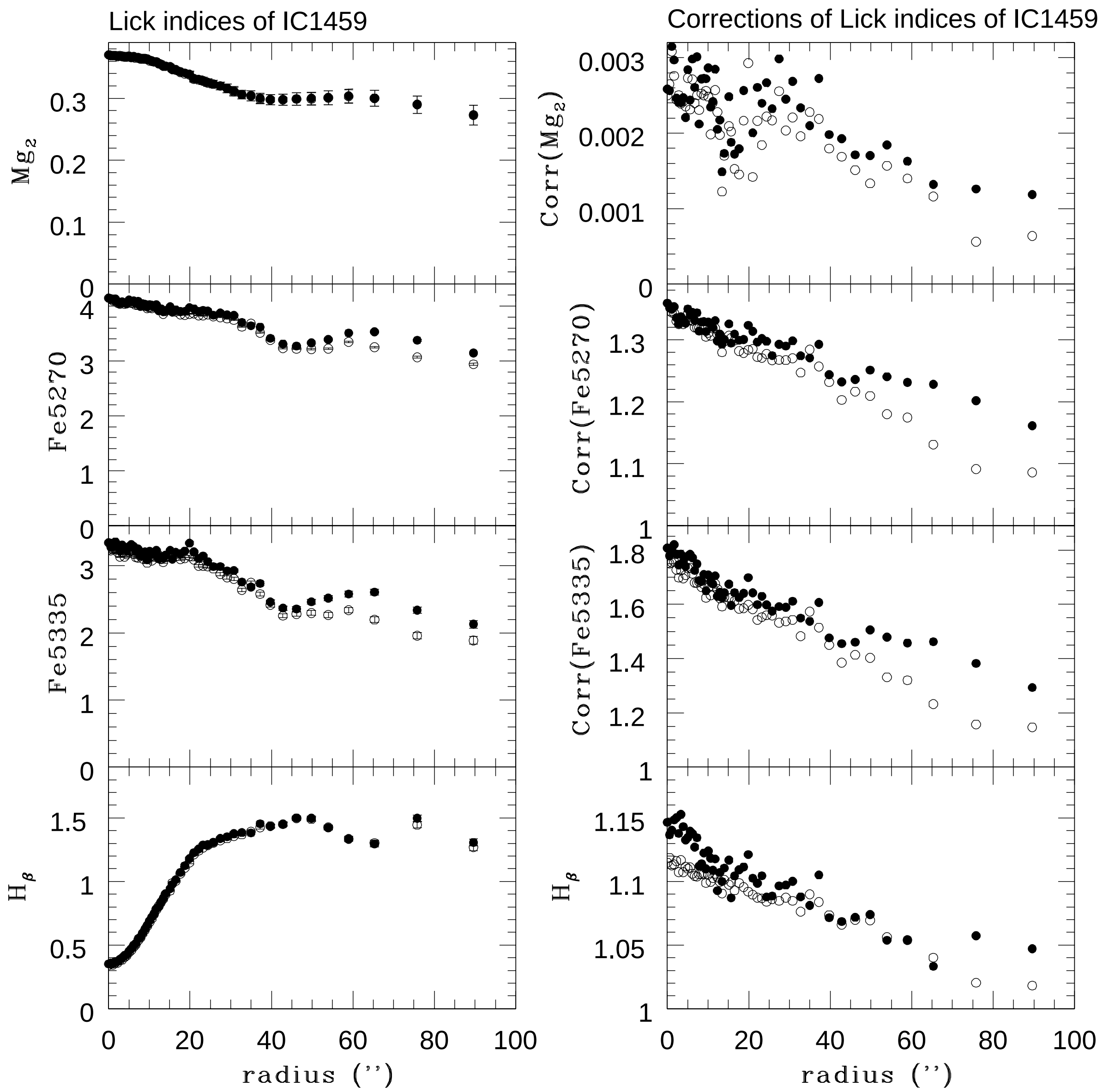

Fig. 2. *Left: Lick indices of the galaxy IC 1459. Open circles denote measurements when correction for dispersion was applied using a pure Gaussian function and the filled circles denote the case when non-zero Gauss- Hermite parameters were taken into account. Note that in the case of* Mg_2 *both values are practically identical. Right: Corrections of the Lick indices presented in the left panel (see text for details). The meaning of the symbols is the same as in the left panel.*

$$C^{\rm GH}(\sigma) = I_{\rm orig} - I^{\rm GH}(\sigma). \quad (7)$$

and for the atomic indices:

$$C^{\rm GH}(\sigma) = I_{\rm orig}/I^{\rm GH}(\sigma). \quad (8)$$

We label the quantities pertaining to a modified Gaussian with an exponent "GH" meaning that they are calculated using non-zero Gauss-Hermite parameters. The results are given in Table 4 and the comparison of two different measurements are presented in Fig. 2 (left panel; the measurements with a modified Gaussian are plotted with full circles).

In Table 5 the corrections of the Lick indices of IC 1459 are given in the tabular form and in Fig. 2 (right panel) they are presented in the graphical form.

4. RESULTS AND DISCUSSION

The results of the measurements of the Lick indices for the elliptical galaxy IC 1459 presented in Tables 3 and 4 and plotted in Fig. 2 (left panel) show their radial profiles. The values of the corrections are given in Table 5 and Fig. 2 (right panel).

The measurements of the molecular, Mg_2, index show that the use of measured Gauss-Hermite parameters does not change the value of the index measured assuming a pure Gaussian: the differences are so small that it is impossible to distinguish them in the plot (left panel of Fig. 2); note that the corrections are visible on a different scale in Fig. 2 (right panel). This means that it is safe to ignore the Gauss-Hermite corrections in calculating the Mg_2 index, even if the h_4 parameter has rather large values as in the case of IC 1459. We also note that the usual corrections (to Lick resolution and to zero velocity dispersion) are very small for the Mg_2 index (see Table 5, column 2).

The results for both iron indices show that beyond $\sim 1R_e$ the differences between two approaches become significant and actually larger than the observational errors (especially for the outermost points). The largest difference is at $r = 75\farcs79$ where the corrections for Fe5270 and Fe5335 are, respectively, ~ 10 and ~ 19 percent larger, when we take into account the non-zero measured values of the Gauss-Hermite parameters h_3 and h_4. Therefore, in case of the Lick iron indices it is incorrect to neglect the impact of anisotropies (when observed), because this inevitably leads to an erroneous estimate (the effect is more pronounced in case of Fe5335). This effect due to anisotropies (i.e. non-zero values of the Gauss-Hermite parameters h_3 and h_4) adds to the already large corrections of the iron indices due to the Lick resolution and zero velocity dispersion known from the literature (which may be up to ~ 35 per cent and ~ 76 per cent for Fe5270 and Fe5335 indices in IC 1459, respectively).

The measurements of the H_β index show that the discrepancies between pure and modified Gaussian measurements are present in the innermost regions (albeit negligible as evidenced in the left panel of Fig. 2) and in the outermost regions (where they are rather small). The introduction of non-zero Gauss-Hermite parameters does not influence much the estimate of the H_β index (the maximal discrepancy is ~ 4 per cent observed at $75\farcs79$). This small effect should be added to usual corrections due to the Lick resolution and zero velocity dispersion which can be as large as ~ 12 per cent (in the innermost regions of IC 1459).

5. CONCLUSIONS

We analysed the measurements of the absorption line-strength Lick indices in the early-type galaxy IC 1459. The long-slit spectra of this elliptical from which its kinematics had previously been extracted (Samurović and Danziger 2005) was used to calculate the following Lick indices available for the observed spectral region: Mg_2, Fe5270, Fe5335 and H_β.

We first presented the full kinematical profile of IC 1459 (velocity, velocity dispersion and the Gauss-Hermite parameters h_3 and h_4) which shows the dominance of the radial orbits in its outer parts as evidenced by rather high values of the h_4 parameter. Then we applied the usual procedure (using our `FORTRAN` software) to calculate the indices which we then corrected to the Lick resolution and also to the zero velocity dispersion. In this work we applied our procedure written in the `IDL` programming language in order to correct the Lick indices for the non-Gaussian line-of-sight velocity distribution observed in this galaxy, especially in its outer parts where the Gauss-Hermite parameter $h_4 >$ reaches the values 0.2.

We tested the findings of Kuntschner (2004) who showed that the departures from the Gaussian LOSVD may cause erroneous determinations of the Lick indices. We showed that the impact of the non-Gaussian LOSVD differs for different indices. For the galaxy IC 1459, it was shown that the iron indices are especially sensitive: the corrections for Fe5270 and Fe5335 are ~ 10 and ~ 19 percent larger than the corrections obtained in the case of a pure Gaussian, respectively. The corrections for Mg_2 index are shown to be negligible and the corrections of the H_β index due to anisotropies are small (below ~ 4 per cent at most).

The overall conclusion that might be drawn is that the effects of anisotropies play an important role in the measurement of the Lick indices. If we neglect these effects (especially when we know them), we are introducing a significant error which is of importance when one wishes to use the Lick indices in various modeling procedures.

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МЕРЕЊЕ LICK ИНДЕКСА У ГАЛАКСИЈАМА РАНОГ ТИПА: КОРЕКЦИЈЕ ЗБОГ ОБЛИКА РАСПОДЕЛЕ БРЗИНА ДУЖ ВИЗУРЕ ЗА ГАЛАКСИЈУ IC 1459

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Оригинални научни рад

У раду се анализира начин рачунања апсорпционих Lick индекса у галаксијама раног типа. Коришћени су спектри са дугачким прорезом (long-slit спектри) елиптичне галаксије IC 1459 за коју су кинематички подаци раније били одређени да би се израчунали Lick индекси за посматрану спектралну област (Mg_2, Fe5270, Fe5335 и H_β). Примењена је уобичајена процедура и индекси су кориговани на Lick спектралну резолуцију и на нулту дисперзију брзина. Процедура која је примењена у овом раду такође коригује индексе и због негаусовске расподеле брзина дуж визуре, која се посебно уочава у спољним областима ове галаксије. Тестирани су резултати Kuntschner-а (2004) и показано је да одступања од гаусовске расподеле брзина може да проузрокује грешке у одређивању Lick индекса. Увођење негаусовске расподеле брзина различито утиче на различите индексе. За галаксију IC 1459 показано је да су индекси који се односе на гвожђе посебно осетљиви када се уводе овакве корекције због анизотропија: корекције за Fe5270 и Fe5335 веће су за ~ 10 и ~ 19 процената, респективно, него корекције добијене у случају када је коришћена "чиста" Гаусова функција. Такође је показано да су корекције за Mg_2 индекс веома мале. Корекције за H_β индекс због анизотропија су такође мале (највише до испод 4 процента).