Line Strengths and Line Strength Gradients in Bulges along the Hubble Sequence*

Paul Goudfrooij
Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD 21218, United States of America (`goudfroo@stsci.edu`)
Affiliated with the Astrophysics Division, SSD, European Space Agency

Javier Gorgas
Departamento de Astrofisica, Facultad de Ciencias Fisicas, Universidad Complutense de Madrid, E-28040 Madrid, Spain (`fjg@astrax.fis.ucm.es`)

Pascale Jablonka
DAEC–URA173, Observatoire de Paris-Meudon, Place Jules Janssen, Meudon, F-92195, France (`pascale.jablonka@obspm.fr`)

Abstract. We present first results of a comprehensive survey of deep long-slit spectra along the minor axis of bulges of edge-on spiral galaxies. Our results indicate that stellar populations in bulges are fairly old and encompass a range of metallicities. The luminosity-weighted ages of bulges range from those found for cluster ellipticals to slightly "younger" (by up to only a few Gyr, however). Their α/Fe element ratio is typically supersolar, consistent with those found in giant ellipticals. The radial line-strength gradients in bulges correlate with bulge luminosity. Generally, these findings are more compatible with predictions of the "dissipative collapse" model than with those of the "secular evolution" model.

Keywords: Bulges of Spiral Galaxies, Stellar Populations, Radial Gradients

1. Introduction: The Formation of Bulges of Spirals

Bulges of spiral galaxies are cornerstones for constraining theories of galaxy formation. Located at the centers of spiral galaxies, they hold the signature of the sequence of formation —outside-in or inside-out— of the different sub-systems building a spiral galaxy: halo, disc, and bulge. The prominence of bulges varies widely along the Hubble sequence. This contrasts with the situation for spiral disks whose mass is nearly constant among all types of spirals (Arimoto & Jablonka, 1992). Hence, bulges constitute a main key to our understanding of spiral galaxy evolution. To set the context for our project, we describe below the two currently most popular scenarios on bulge formation that have been proposed over the years.

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* Based on observations obtained at ESO, La Silla, Chile (Observing Programmes 58.A-0192, 59.A-0774, and 61.A-0326), and at the Isaac Newton Telescope operated on the island of La Palma by the Isaac Newton Group in the Spanish Observatorio del Roque de los Muchachos of the Instituto de Astrofisica de Canarias

Monolithic Dissipative Collapse: Bulges form before disks do, on very short time scales. As the pregalactic gas collapses and forms stars, metals are ejected by winds blown by massive stars and supernovae. If the galaxy potential well is deep enough to retain these ejecta, the enriched gas is carried inward to the galaxy center. As new stars are formed, their chemical composition reflects that of the gas. The result is a radial metallicity gradient, whose amplitude should increase with galaxy mass and luminosity (Carlberg, 1984; Arimoto & Yoshii, 1987).

Evidence in favor of this scenario has been presented by means of spectroscopic studies of *ellipticals*: Carollo, Danziger & Buson (1993) reported the presence of a correlation between radial Mg_2 absorption-line-strength gradients and galaxy mass, velocity dispersion, and central line strength for low– to intermediate-mass (*i.e.*, $\mathcal{M} \lesssim 10^{11}\mathcal{M}_\odot$) ellipticals, as opposed to *giant* ellipticals (but see different results by González & Gorgas 1996 and Kobayashi & Arimoto 1999). The gradients may thus be driven mostly by dissipation in smallish ellipticals, whereas merging and violent relaxation play a more important role for giant ellipticals. What about the actual case of bulges of spirals ? There is strong evidence that bulges are analogous to low– to intermediate-mass ellipticals in several *global* principal properties: they populate the same location in the Fundamental Plane (Bender, Burstein & Faber, 1992); they form a continuous sequence in the V_{max}/σ_0 vs. ellipticity diagram (being supported by rotation, Bender et al. 1992). As to the stellar populations, Jablonka, Martin & Arimoto (1996) performed a spectroscopic pilot study of the centers of bulges of face-on spirals. They revealed the existence of striking similarities between bulges and ellipticals. *E.g.*, their luminosity-metallicity relations, when derived from α-elements (such as the Mg_2 index), are consistent with one another.

Secular Evolution: Bulges form from disc material through redistribution of angular momentum. In this scenario, large amounts of gas are driven into the central region of the galaxy by a stellar bar and trigger intense star formation (*e.g.*, Pfenniger & Norman 1990). If enough mass is accreted, the bar itself will be dissolved and the resulting galaxy will reveal a bigger bulge than before bar formation; galaxies would thus evolve from late to earlier types along the Hubble sequence.

This model also certainly has its attractions. Bars appear in at least $\sim 2/3$ of disk galaxies (Sellwood & Wilkinson, 1993), and several numerical simulations have indicated that bars can significantly influence the dynamical evolution of galaxies, through mechanisms such as disk thickening by box-peanut or bending instabilities (Combes et al., 1990) or radial mass inflow towards the center (Friedli & Benz, 1995). Since bars appear to be able to affect the global dynamics of galaxies, it is natural to suspect that bars can be responsible for significant chemical evolution as well, due to mixing by the bar-induced kinematics. Recent N-body simulations (that include the effect of star formation) have shown this to be a valid suspicion in the sense that any initial abundance gradient is indeed significantly washed out ~ 1 Gyr after formation of a bar, both for gas and stars (Friedli, Benz & Kennicutt, 1994; Friedli, 1998). The slope of the abundance gradient is found to flatten beyond the co-rotation radius, by up to $\sim 50\%$ through the effect of one (strong) bar. Observational evidence for this effect exists, albeit only for the gas component so far. Several groups have shown that global radial gradients of the gas metallicity (in terms of [O/H] in H II regions) in barred spirals are shallower than gradients in "normal" spirals of the same Hubble type (Vila-Costas & Edmunds, 1992; Zaritsky et al., 1994; Martin & Roy, 1994). Furthermore, a clear relation seems to exist between the relative length of the bar with respect to the size of the (optical) disk and the slope of the radial [O/H] gradient among barred spirals (Martin & Roy, 1994) in the sense that the larger the bar/disk ratio, the shallower the abundance gradient.

1.1. LINE-STRENGTH GRADIENTS: KEY TO THE CONTROVERSY?

It thus seems that radial population gradients in bulges have great potential in discriminating between the main bulge formation scenarios. Previous work on stellar populations in bulges has mainly been limited to photometric studies: Balcells & Peletier (1994) in UBRI, and Terndrup et al. (1994) in J and K, show that for luminous bulges, color gradients become increasingly negative with increasing luminosity (similar to the case among ellipticals). However, many faint bulges deviate from this trend and keep showing strong negative color gradients, and the two studies mentioned above do not converge in their conclusions. Besides, it is now well known that broad-band photometry is incapable of accurately disentangling the effects of age, metallicity, and dust absorption, whereas stellar line strenghts are dust-independent and *can* separate the effects of age and metallicity (*e.g.*, Worthey, 1994, hereafter W94; Vazdekis et al., 1996). With this in mind, we embarked on a spectroscopic survey of a significant sample of bulges to compare their possible star formation histories with those in ellipticals.

2. Description of our Project

In order to avoid contamination from disk light, we selected a sample of 28 edge-on, nearby spiral galaxies from the UGC and ESO-LV catalogs, and oriented the spectrograph slit along the minor axis of the bulges. The sample encompasses a considerable range in luminosities for each Hubble type ($18.4 < -M_V < 21.5$). The observations (spectroscopy and two-color imaging) of the northern spirals were obtained with the

2.5-m Isaac Newton Telescope at La Palma, while the southern spirals were observed with the ESO NTT and 3.6-m telescopes. As to the spectroscopy, the typical exposure time was ~ 4 hours per galaxy, and the instrumental resolution was typically of order 100 km s^{-1}. The spectral range used (typically 3900 − 5500Å) allowed the measurement of most Lick/IDS line-strength indices.

All spectral data reduction and line index measurements were performed using the $\mathrm{R_E D^{UC}_{M} E}$ package[1] which propagates errors associated with all reduction steps along with the science data. The line indices were fully calibrated to the Lick/IDS system (including broadening corrections), using measurements of ~ 40 IDS standard stars (Gorgas et al., 1993). Full details of the sample selection, the observations, and the calibrations will be provided in a forthcoming paper.

3. Results

At the time this paper is written, data analysis of 16 bulges in our sample is completed. Here we describe some highlights of the results from this subsample.

3.1. Central Line Strengths

In order to effectively compare "central" line strengths for bulges with those of ellipticals in the literature, we extracted spectra with spatial extent $4''$ from the galaxy center *but avoiding the innermost dust lane* to eliminate disk light. In disentangling the effects of age and metallicity, most authors have used a combination of Hβ and "metallic" line-strengths such as $\mathrm{Mg_2}$, Mg b, Fe5270 and Fe5335 (*e.g.*, González 1993). However, the use of the Hβ and Mg b indices is very limited in case nebular emission is present (Goudfrooij & Emsellem, 1996), which is "unfortunately" often the case in our spectra. We did not attempt to correct Hβ for emission, but rather used the Hγ_A index as age-sensitive index (calibrated in age/metallicity space by Worthey & Ottaviani 1997). Since the relative strength of Balmer line emission decreases rapidly with Balmer order (*e.g.*, Osterbrock 1974), Hγ_A is significantly less diluted by nebular emission than Hβ is.

In Fig. 1 we present plots of the Hγ_A index vs. two metallicity indicators: *(i)* $\mathrm{C_2}$4668 which Jones & Worthey (1995) identified as a particularly metallicity-sensitive index, and *(ii)* $<\mathrm{Fe}> = (\mathrm{Fe5270}+\mathrm{Fe5335})/2$. For comparison, we also plot the results of Kuntschner & Davies (1998; hereafter KD98) for the centers of E and S0 galaxies in the Fornax cluster, as well as predictions from single-burst population synthesis models (W94; Worthey & Ottaviani 1997). It turns out that the bulges

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[1] Cardiel & Gorgas, http://www.ucm.es/info/Astrof/reduceme/reduceme.html

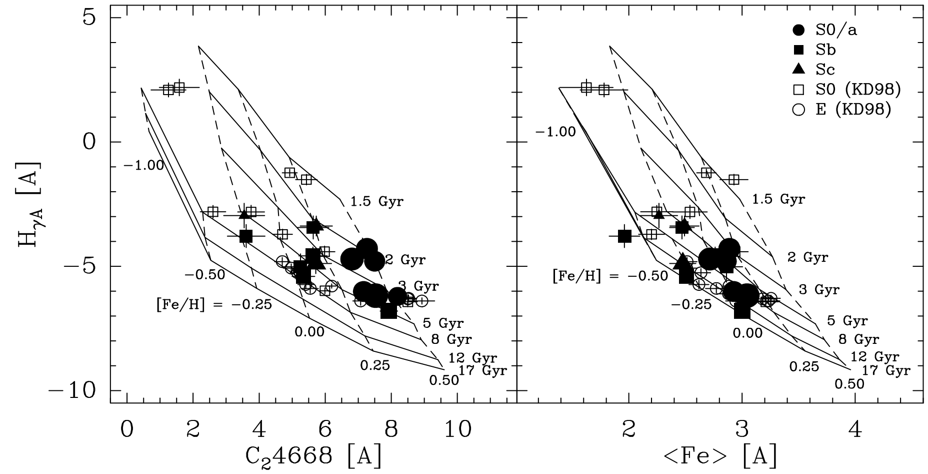

Figure 1. The age-sensitive index $H\gamma_A$ is plotted against metallicity indicators $C_2$4668 *(left)* and $<$ Fe $>$ *(right)* for the central regions of bulges in our sample. Age-metallicity grids from population synthesis models by Worthey (1994) and Worthey & Ottaviani (1997) are overplotted. Solid lines represent constant age, while dashed lines represent constant metallicity. Symbol definitions are shown in the inset; symbol size is proportional to the bulge luminosity. Open circles and open squares represent centers of Fornax ellipticals and S0s, respectively, from KD98.

in our sample have ages similar to (or up to a few Gyr "younger"[2] than) those of *cluster* ellipticals. On the other hand, luminosity-weighted ages of a sample biased towards *field* ellipticals (González 1993) span the whole range found for bulges. The metallicities of bulges cover a range similar to those of ellipticals. Interestingly, bulges of later-type (Sb – Sc) spirals are, in the mean, less metal rich than their counterparts in earlier-types. This seems to be a bulge luminosity effect, judging from the symbol sizes in Fig. 1. There are no other obvious distinctions between bulges of different Hubble types in this context.

Another interesting point is that, comparing the positions of the galaxies in Figs. 1a and 1b, it appears that C_2 (*i.e.*, the $C_2$4668 index) is overabundant in ellipticals and bulges with respect to solar abundance ratios. This is illustrated in Fig. 2a which compares $C_2$4668 with $<$ Fe $>$. Comparing the observations with the superimposed models of W94, it is obvious that $C_2$4668 is stronger than indicated by the models (which employed solar abundance ratios). Whether this is a real overabundance effect (or, *e.g.*, due to a problem in the fitting functions) is an issue which deserves further analysis.

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[2] Recall however that line-strength indices reflect *luminosity-weighted* properties in a galaxy. A young population that is small in mass —but relatively large in luminosity—, can dramatically change the index values.

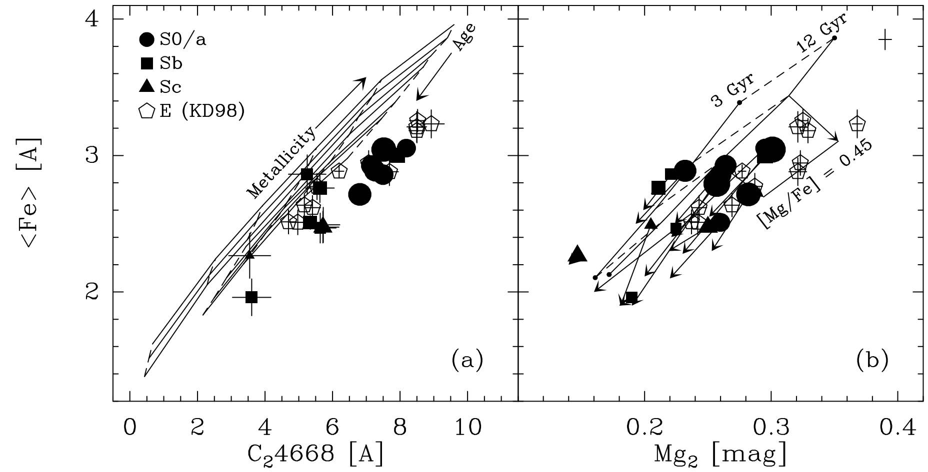

Figure 2. *(a)* C_24668 vs. $< \mathrm{Fe} >$ indices for the central regions of bulges in our sample. Models by Worthey (1994) are overplotted as in Fig. 1. Symbols are shown in the inset. The symbol size is proportional to the bulge luminosity of the galaxies. Open pentagons represent Fornax ellipticals from Kuntschner & Davies (1998). *(b)* Mg_2 vs. $< \mathrm{Fe} >$ indices for bulges in our sample. Symbols as in Fig. 2a. The filled symbols represent the "central" indices of the bulges, and the arrows pointing downwards from those symbols denote the radial (vertical) gradients going outwards (length of arrow is proportional to the gradient slope). Overplotted are models by Worthey (1994) [only for ages 3 and 12 Gyr; solid lines] and a correction for [Mg/Fe] = 0.45 for the 12 Gyr isoage line (calculated from models by Weiss et al. 1995).

3.2. Radial Line-strength Gradients

Fig. 2b shows a $<\mathrm{Fe}>$ vs. Mg_2 plot for the bulges in our sample. The symbols depict the "central" values, while the arrows point towards the outermost well-measured values; the length of the arrows is a measure of the slope of the gradient. It is clear that, in most bulges, Mg is overabundant with respect to solar abundance ratios. The [Mg/Fe] abundance ratio in bulges is similar to those found in ellipticals, and stays more or less constant throughout the radial extent of bulges. From the (overplotted) α-element-overabundance models by Weiss, Peletier & Matteucci (1995) for [Mg/Fe] = 0.45 and an age of 12 Gyr (and mixing length parameter $\alpha_{\mathrm{MLT}} = 1.5$), we estimate that [Mg/Fe] $\lesssim 0.4$.

Is there a correlation between the metallicity gradient and luminosity for bulges, as predicted by dissipative collapse models ? This relation is depicted in Fig. 3. Bulge luminosities[3] were derived by performing ellipse fits to the isophotes of the galaxy images, after masking out wedges encompassing the dusty disks (± 20° from the major axes). The gradient-luminosity correlation indeed exists; any further distinction

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[3] using $H_0 = 50$ km s^{-1} Mpc^{-1}

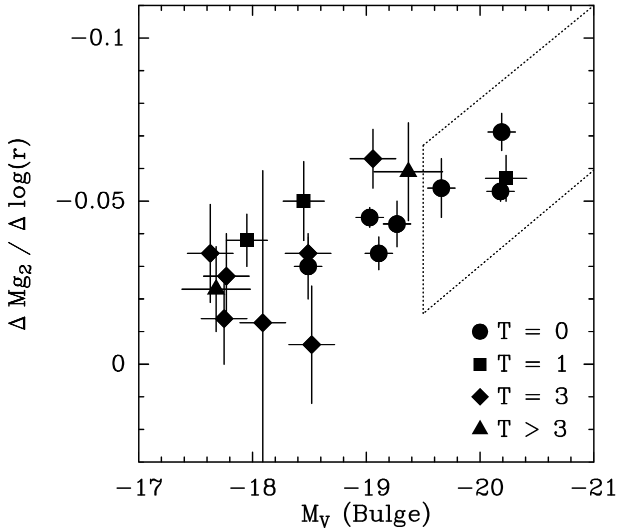

Figure 3. Logarithmic radial gradient of Mg_2 index vs. absolute V-band **bulge** luminosity of the bulges analyzed to date. Symbols are shown in the inset (where T is the RC3 morphological type). The dotted lines depict the extremes of the $\Delta Mg_2/\Delta \log(r)$ vs. M_V relation among low– and intermediate-luminosity E and S0 galaxies from Carollo et al. (1993).

between bulges of different Hubble types within this relation is not obvious. Incidentally, the Mg_2 gradients of the most luminous bulges as well as the slope of the gradient-luminosity relation are similar to those among low-luminosity ellipticals in the Carollo et al. (1993) sample.

4. Concluding Remarks

From the spectral data of bulges of spirals in our sample analyzed so far, we have established the following main results:

1. Bulges have luminosity-weighted metallicities varying from roughly −0.50 to +0.20 in [Fe/H], as measured from $H\gamma_A$ vs. $<$Fe$>$ index diagrams. Many bulges are as old as cluster ellipticals, but some (low-luminosity) bulges have luminosity-weighted ages up to a few Gyr younger (note that this result may be influenced by residual light from thick disks).
2. Bulges are typically overabundant in α-elements, up to [Mg/Fe] $\simeq +0.4$ dex, throughout their radial extent. There is no obvious correlation between [Mg/Fe] and bulge luminosity. This is similar to the situation among ellipticals, and indicates that the bulk of the stars in bulges typically formed within a few Gyr (before the onset of SNIa explosions; *e.g.*, Worthey, Faber & González 1992).
3. There is a correlation between the radial metal-line index gradients and the bulge luminosities for bulges in our sample.

These first results seem to be generally more compatible with the predictions of the "dissipative collapse" models than with those of the "secular evolution" models (cf. Sect. 1). However, some individual bulges seem to be younger than the rest and show shallow radial $\mathrm{Mg_2}$ gradients, which in turn can be due to effects induced by bar instabilities. Moreover, we postpone the announcement of "final" conclusions until the data of our full sample of 28 bulges has been analyzed.

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