STELLAR POPULATIONS IN S0 GALAXIES

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1. Introduction

The study of stellar populations in external galaxies has so far concentrated on elliptical galaxies, spirals and a few dwarf galaxies, while S0 galaxies found only relatively little attention (with a few notable exceptions, e.g., Gregg, 1989; Bothun and Gregg, 1990). This is astonishing because S0-galaxies offer a unique possibility to study (a) old disk populations outside our own galaxy, (b) the properties of bulges in external galaxies without contamination by blue disk stars, and (c) the gradual change of the stellar populations of galaxies as a function of disk-to-bulge ratio. Last but not least, the comparison of the stellar populations of ellipticals, spirals and S0 galaxies allows to re-iterate on the question whether S0's are principally similar to spirals but have just stopped forming stars earlier, or, whether they form an class intermediate between ellipticals and spirals (e.g.Larson *et al.*, 1980; van den Bergh, 1994).

In this paper, we want to present the results of an analysis of the stellar populations in 17 S0 galaxies. Most of the objects were selected to be edge-on in order to allow a better separation between disks and bulges and also to allow to probe the population gradients in the disks to large radii. For comparison and calibration purposes we furthermore observed 16 ellipticals, most of which have previously been analysed by Peletier (1989), Gorgas *et al.* (1990), Davies *et al.* (1993), Carollo *et al.* (1993) and Gonzalez (1993).

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2. Observations and Data Analysis

The data for our study were obtained between 1991 and 1993 in four observing runs at the Calar Alto 2.2m telescope which was equipped with a Boller and Chivens longslit spectrograph and a GEC CCD. The spectral resolution corresponded to $\sigma_{instrum} \approx 180\,\mathrm{km/s}$. From the two-dimensional spectrograms we measured radial profiles of absorption line strengths of Ca, CN, Mg, Na, Fe and the Balmer lines between 3800Åand 6500Åusing the Lick system of absorption indices (Faber *et al.*, 1985; Burstein *et al.*, 1984). The index measurements were calibrated using the standard stars from Faber *et al.*'s list and from Gonzalez (1993) and were corrected for velocity dispersion broadening. The rotation velocities and velocity dispersions were measured using the Fourier Correlation Quotient method (Bender 1990). The reliability of the obtained velocity dispersions was checked using results from Seifert (1990) who observed the same objects with higher spectral resolution.

3. Metallicity Gradients in S0 Disks

The information about metallicity gradients in galaxy disks relies until to date almost exclusively on emission line analysis of HII regions (e.g. Pagel and Edmunds, 1981; Vila-Costas and Edmunds, 1992; Zaritsky *et al.*, 1994). The inferred metallicity gradients are of the order of -0.2 dex per e-folding (or scale) length or about -0.06 dex per kpc of the disk with very large scatter. Only in our own Galaxy a metallicity profile could also be derived for the stellar component. However the results turn out to be ambiguous: while old field K giants were found to exhibit no significant gradient (Edvardsson *et al.*, 1993), old open clusters do show a gradient of -0.09 dex/kpc (Friel and Janes, 1993). The probably most reliable analyses (Gehren *et al.*, 1985; Kaufer *et al.*, 1994) refer to the abundance gradient in B stars which again turns out to be very small. The latter measurements are in clear conflict with the abundance gradients derived for the gas of our own Galaxy (e.g., Shaver *et al.*, 1983) or external galaxies (see above). Whether the difference is real or partly due to measurement problems (e.g. inaccurate temperatures) is unclear at present. Theoretically, there is still conflicting predictions what amplitude the metallicity gradients in galactic disks should show (Lacey and Fall, 1985; Matteucci and Francois, 1989; Josey and Arimoto, 1992).

For these reasons it is interesting to analyse the line strength gradients in the disks of S0 galaxies. As a rather typical example for these objects, we show in Fig. 1 the surface brightness profile and profiles of Mg_b, CN_1, <Fe> (the mean EW of the Fe lines at $\lambda = 5270$ Åand $\lambda = 5335$ Å) and H_β along the major axis of the galaxy NGC 7332. It is evident that in the radius range

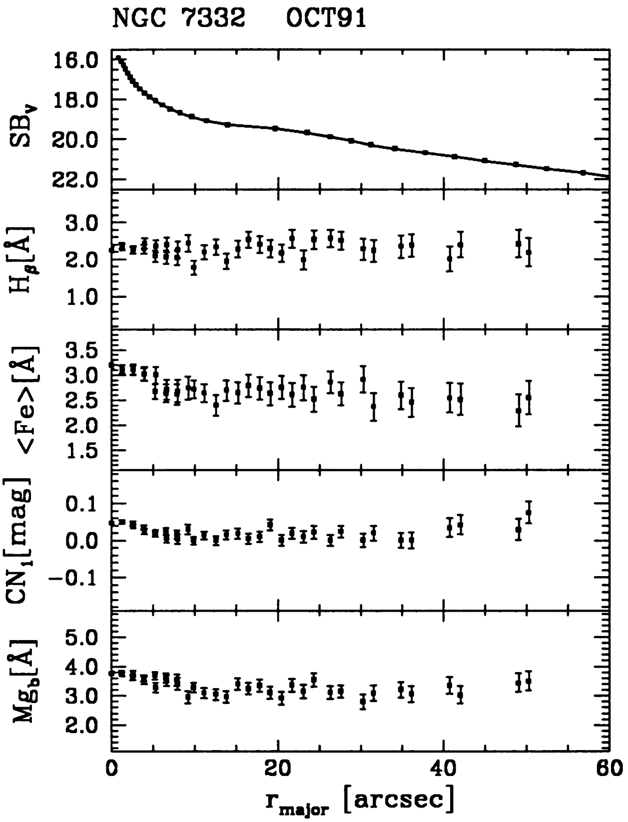

Figure 1. Surface brightness and line strengths along the major axis of NGC 7332.

where the disk dominates ($r >$ 10"≈ 1 kpc) no significant gradient in any of the indices is observed. Principally, there are two interpretations for this finding: (a) the disk has radially constant metallicity and age, or, (b) there is a fine-tuned ballance between the metallicity gradient and the age gradient. Since option (b) is unlikely because such a perfect compensation can only exist for a relatively short period of time we conclude that option (a) is the most plausible interpretation. Also, if an age gradient were present, we would expect the disk to be younger in the outer parts which would imply – in order to obtain radially constant line strengths – that metallicity must increase with radius, a rather unlikely possibility.

Adopting a radially constant age for the disk in NGC 7332, we can calculate upper limits for the metallicity gradient from the metal line profiles using population synthesis models by Worthey (1992, 1994, these models predict absorption line strengths for simple stellar populations as a function of metallicity and age). For populations with an age between 4 Gyr and 12 Gyr and metallicities between 1/3 and 3 times solar these models give (independent from age):

$$\frac{\delta \mathrm{Mg_b}}{\delta \log \mathrm{Z}} \approx 2.3, \quad \frac{\delta \mathrm{CN_1}}{\delta \log \mathrm{Z}} \approx 0.12, \quad \frac{\delta < \mathrm{Fe} >}{\delta \log \mathrm{Z}} \approx 1.7, \quad \frac{\delta \mathrm{H}_\beta}{\delta \log \mathrm{Z}} \approx -0.65$$

From these relations we obtain $\Delta[Z/H] < -0.06$ dex per scale length or < -0.03 dex per kpc in NGC 7332.

NGC 7332 is, as already mentioned, a quite typical object in our sample. However, there also exist S0's with significant metallicity gradients (again adopting radially constant age in the disk). E.g., in NGC 3098, we derive consistently from all metal lines a gradient of -0.10 ± 0.3 dex per scale lengths or -0.07 ± 0.2 dex per kpc. **On average, our sample of S0 disks shows a metallicity gradient of: $\Delta[\mathbf{Z/H}]/\Delta(\mathbf{r/r_s}) \approx -0.06 \pm 0.04$,** with r_s denoting the scale lengths of the disks. This value is about a factor three smaller than the typical metallicity gradients measured in the gas of spiral galaxies (Zaritsky *et al.*, 1994). So, either the metallicty gradients become weaker with increasing age (and decreasing gas-to-star ratio), or, there exists a principle difference between gaseous and stellar gradients, as it may be the case in our own Galaxy.

4. Ages of S0 Bulges *vs.* S0 Disks

Inferring absolute ages and metallicities from line strengths of integrated stellar populations is in principal possible but at present still rather uncertain (see, e.g., Bothun and Gregg, 1990, for an attempt to age-date S0 disks). The reasons are several, like, e.g., insufficient understanding of certain stages of stellar evolution (especially for metal-rich stars), incompleteness of stellar libraries, or, neglecting late phases in stellar population synthesis models. Differential measures are fortunately much more reliable (e.g. Worthey, 1994) and so we can quite reliably compare the relative ages and metallicities of disks and bulges in S0 galaxies.

As an example, we again discuss NGC 7332 (Fig. 1). Inside of 10 arcsec the stength of the Fe and Mg lines increases by about 20%, while H_β remains constant. There are again two options to explain this behaviour:

(a) The bulge is older than the disk but of similar metallicity. This explains the CN, Mg and Fe profiles but appears inconsistent with the H_β profile because smaller age for the disk would imply stronger H_β. One way out of this dilemma is to assume that the H_β absorption is weakened throughout the disk by H_β *emission*. Although weak emission is indeed present in some parts of NGC 7332, it is not smoothly distributed and mostly present in the bulge region (see also Bertola *et al.*, 1992; Fisher *et al.*, 1994). Therefore the young-disk/old-bulge interpretation is inconsistent with the data.

(b) The bulge is both more metal rich and younger than the disk. This explains the higher metal absorption lines in the bulge *and* also why H_β does not decrease with increasing metal line strengths inside 10arcsec. In fact, H_γ and H_δ do even increase in the bulge region supporting the claim that the bulge is indeed younger (H_γ and H_δ are less affected by emission).

Based on this reasoning, we have to conclude that in NGC 7332 the bulge is most likely younger than the disk. Morphologically, the bulge of NGC 7332 is not exceptional but it is clearly boxy and its apparent major axis is inclined with respect to the projected major axis of the disk. Bertola *et al.* (1992) and Fisher *et al.* (1994) showed that the emission line gas in NGC 7332 is kinematically de-coupled and is indicative of an accretion event which may be relted to the younger bulge.

Among our sample of S0-galaxies, there are a few other galaxies which show exactly the same indications for a younger bulge as NGC 7332. Hibbard and Rich (1990) even have found evidence for an extremely young bulge in NGC 5102, i.e. the bulge has an A-type spectrum. Whether younger bulges can be created in interaction or accretion events with small satellite galaxies, or, whether they are formed from disk instabilities (e.g. Combes *et al.*, 1990; Raha *et al.*, 1991) with associated star formation can only be answered by theoretical modelling and further observational data.

5. Element Ratios in S0 Disks and Bulges

We know that the old stars in the Galactic disk show roughly solar element ratios. Especially telling is the ratio of light elements to iron-peak elements because it implies that SNI and SNII have about contributed equally to the enrichment to the disk stars in the solar neighborhood (e.g., Matteucci, 1991). There is now strong evidence that this is not the case in all galaxies. Peletier (1989), Faber *et al.* (1992) and Davies *et al.* (1993) found that in elliptical galaxies Mg is overabundant relative to Fe by roughly a factor three (see Faber, this conference). A similar overabundance of Mg over Fe is apparently also present in the Galactic bulge (Terndrup, 1993; McWilliam and Rich, 1994).

In view of these results it is interesting to see what element ratios in the disks and bulges of S0's are found. Especially, it has to be noted that, so far, basically nothing is known about the light-element to iron abundance in external disks at all.

Fig. 2 shows the relationship between local Mg_b and local <Fe> for a selection of elliptical and S0 galaxies from our sample. We plotted only those S0s for which bulges and disks can unambiguously be separated. The filled squares correspond to measurements in the bulges (which may still be partly contaminated by disk light) and the open squares to those in the disks; the crosses represent the ellipticals of our sample for compari-

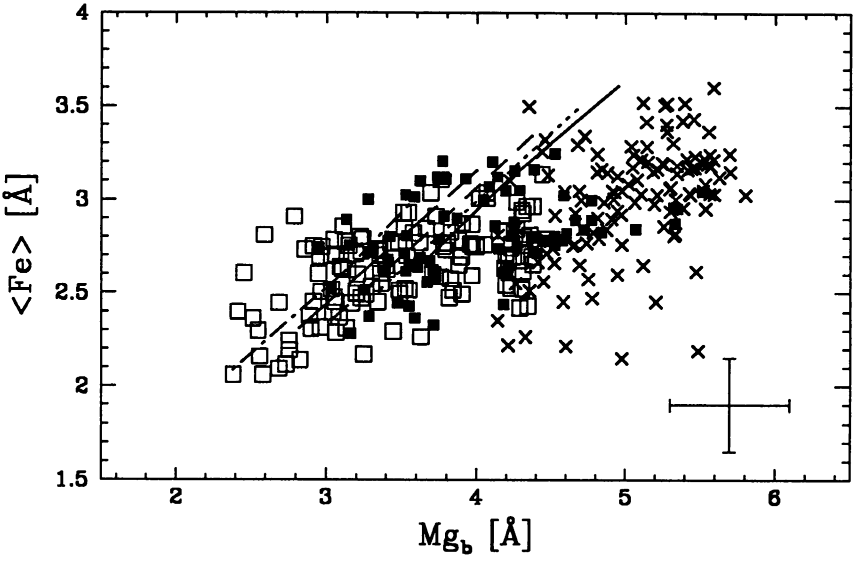

Figure 2. Local Mg$_b$ vs. <Fe> of S0 disks (open squares), S0 bulges (filled squares) and ellipticals (crosses).

son, they exhibit the well-known Mg overabundance. The lines represent population synthesis models by Worthey (1994) which have solar element ratios; each line corresponds to a single age of 3, 5, 8, 12, or 17 Gyrs, and metallicity is varying from -0.3 dex to +0.3 dex along each line. It is evident that most disk points are within the error bars consistent with solar element ratios. The bulges show a large spread in behaviour, some seem to have Mg overabundance (with [Mg/Fe] up to ≈ 0.5, similar to ellipticals), others solar element ratios. If overabundance is found in Mg, we also find overabundance in CN and Na (not shown here), *i.e.* it seems to be indeed the case that all light elements are overabundant by a similar factor. This shows that the enrichment of these bulges was dominated by SNII and massive stars, while the role of SNI element input is relatively smaller than in the disks.

There is a hint from our data that *those bulges that have solar element ratios may also be the ones which are of similar or less age than their accompanying disks.* However, the latter result needs further data to be confirmed.

6. Global Metallicities of S0 Disks and Bulges

Elliptical galaxies and bulges of S0 and Sa galaxies are known to follow a rather tight correlation between Mg absorption and velocity dispersion (Bender, 1992; Bender, Burstein and Faber, 1994). Likewise, the metallicity

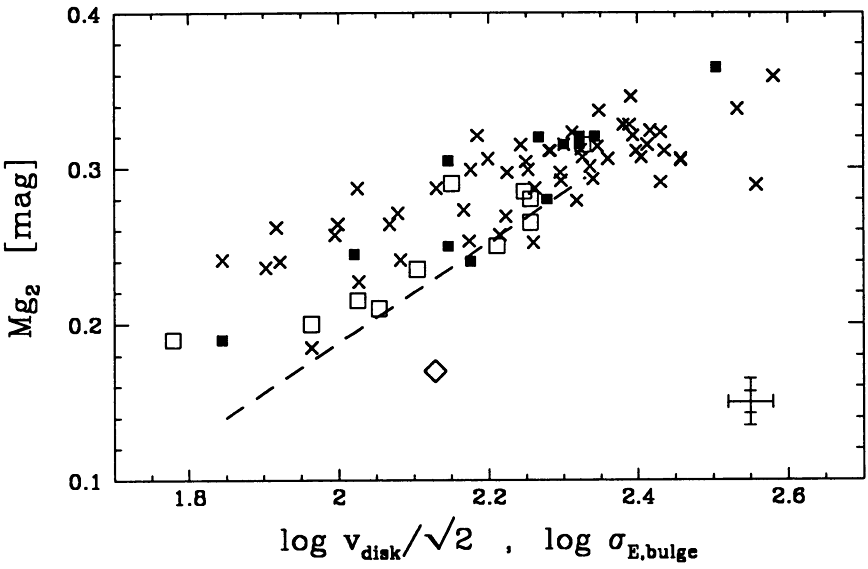

Figure 3. Global Mg absorption vs. velocity dispersion or rotation velocity for S0 disks (open squares), S0 bulges (filled squares), ellipticals (crosses) and spiral disks (dashed line).

of the gas in spiral disks also is correlated with the circular velocity of these galaxies (Zaritsky *et al.*, 1994). How do S0 disks fit into this picture?

As Fig. 3 shows, *S0 disks (open squares) do indeed seem to follow a very similar relation between mean Mg$_2$-index and velocity dispersion as bulges (filled squares) and ellipticals (crosses)* (rotation velocities of the disks were transformed into fiducial velocity dispersions assuming an isothermal potential: $\sigma = v_{\rm disk}/\sqrt{2}$). Again, we only plotted those S0 galaxies where a clear separation between bulges and disks was possible. Only one S0 disk deviates significantly from the relation (the diamond in Fig. 3) and this is the disk of NGC 5866 which shows very strong H_β absorption and other evidence for the presence of stars earlier than type G.

We can still go one step further and can also try to compare with spiral galaxies. For this purpose we have to transform the mean metallicities of spiral disks from, e.g., Zaritsky *et al.* (1994) into fiducial Mg$_2$ indices. This can be 'done' by stopping star formation, aging the spiral disks to, say, a mean age of 8 Gyr and using Worthey's models to derive Mg$_2$ values for each metallicity. The resulting Mg$_2$ – σ relation for spiral disks is given by the dashed line shown in Fig. 3. It very closely matches the distribution of the points corresponding to the S0 disks, not only with respect to slope but also with respect to zero point. This result is very remarkable, not only because of our crude transformations of kinematic and population quantitites to obtain similar parameters for all objects, but even more so because it follows that the metallicity of a stellar population does neither seem to depend significantly on galaxy type, nor kinematic structure, nor gas-to-star ratio. Mean potential depth or total mass seem to to be the most important parameters for determining the enrichment of a galaxy.

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WHITE: I don't understand why the fact that the bulges of some of your galaxies appear younger than their disks should favour formation by bar–induced instability of the flattened component. Such instabilities are stellar dynamical and so don't change the ages of stars.

BENDER: Certainly, this will be a complex process. But one may envisage that an encounter that triggers bar formation must likely also trigger star formation (since the bar will enhance cloud–cloud collissions as well). If the bar sunsequently thickens this might add young stars to a bulge. Consider, that we are only able to estimate *mean* age differences between bulge and disk. So, apparently young bulges may consist in fact of an old plus a young component. Besides bulge formation via disk instability one may of course also create bleu bulges via accretion of satellite galaxies, at least in principle.

WHITE: I think the enhanced abundance (relative to solar) of α–elements relative to iron in elliptical galaxies cannot be ascribed to rapid formation and the resulting loss of iron from Type I supernavae. This is because the ICM in rich clusters is *also* seen to be enriched in α–elements relative to iron. Since the overall system ICM + galaxies should approximate a closed box, the overall [Mg/Fe] should approximate the yield averaged over 10^{10} yrs. This yield clearly must be more α–rich than the time–averaged yield in the Galaxy. Apparently, the mean IMF averaged over a cluster must differ substantially from the Galactic IMF.

BENDER: Treu, the IMF may be very top heavy and thus light element overabundance can be created as well. However, there is an upper limit to [Mg/Fe] that is set by the iron production of SNII, which s likely around 0.5, as we know from our Galaxy. So, if the overabundance of light elements is very high one may really need short star formation timescales (provided that not more exotic processes like low binary fraction or highly selective mass loss play a role). How this can be matched with the abundances in the X–ray gas of clusters, I have no clue.