Integrated Stellar Populations of Bulges:
First Results

By S. C. TRAGER\(^1\), J. J. DALCANTON\(^2\),
AND B. J. WEINER\(^1\)

\(^1\)Carnegie Observatories, 813 Santa Barbara Street, Pasadena CA 91101
\(^2\)Department of Astronomy, University of Washington, Box 351580, Seattle WA 98195-1580

We present first results from an on-going survey of the stellar populations of the bulges and inner disks of spirals at various points along the Hubble sequence. In particular, we are investigating the hypotheses that bulges of early-type spirals are akin to (and may in fact originally have been) intermediate-luminosity ellipticals while bulges of late-type spirals are formed from dynamical instabilities in their disks. Absorption-line spectroscopy of the central regions of Sa–Sd spirals is combined with stellar population models to determine integrated mean ages and metallicities. These ages and metallicities are used to investigate stellar population differences both between the bulges and inner disks of these spirals and between bulges and ellipticals in an attempt to place observational constraints on the formation mechanisms of spiral bulges.

1. Introduction

Current thinking considers two major pathways to the formation of spiral bulges. Simplicistically, either the bulge formed before the disk (“bulge-first,” e.g. van den Bosch 1998), or formed from the disk (“disk-first,” e.g., Combes & Sanders 1981). Previous studies have shown that bulges of big-bulge spirals (like M31) share at least some stellar population properties with mid-sized elliptical galaxies. They fall along the \(D_n–\sigma\) relation (Dressler 1987) and the Fundamental Plane (Bender, Burstein & Faber 1992). Moreover, Jablonka et al. (1996) and Idiart et al. (1996) find that bulges of spirals (as late as Sc) fall along the \(Mg–\sigma\) relation defined by early-type galaxies, suggesting that bulges share a mass-metallicity relation with elliptical galaxies. Together with kinematical evidence, these observations have led to the idea that mid-sized ellipticals accrete disks from some leftover gas reservoir, forming spiral galaxies (see, e.g., Kauffmann, White & Guiderdoni 1993). Therefore, the stars in spiral galaxy bulges should be similar to the stars in ellipticals (i.e. metal-rich, high \([Mg/Fe]\); e.g., Worthey, Faber & González 1992; Trager et al. 1998b) and unlike the stars in spiral galaxy disks.

Kinematical and surface brightness observations of small-bulge spirals indicate that their bulges share many properties with their disks: Many bulges in these spirals are better represented by a shallower exponential profile than by the steep de Vaucouleurs profile (e.g., de Jong 1996) and many of these bulges exhibit disk-like kinematics (see Kormendy 1993 for an excellent review). Moreover, Peletier & Balcells (1996) and de Jong (1996) find that the color difference between bulge and disk in an individual galaxy is much smaller than the variation in colors across galaxies of a single Hubble type.\(^\dagger\) These observations have led these authors and others to propose that bulges (of small-bulge spirals at least) are formed from the stars already present in their underlying disks. That is, the stars in spiral galaxy bulges should be similar to the stars in spiral galaxy disks.

\(^\dagger\) However, very recent observations by Peletier & Davies (this meeting), using HST WFPC2 and NICMOS imaging of the Peletier & Balcells sample of early-type spirals, have shown that bulges are uniformly red, suggesting that the bulges are uniformly old and metal-rich. Clearly these issues are by no means settled with current observational data.
disks (e.g., ages and metallicities of their inner disks, solar [Mg/Fe]) and unlike stars in ellipticals.

These two scenarios do have testable consequences, and sophisticated techniques now available can provide definitive answers to these questions. We have embarked on a multi-year survey to probe the stellar content of the bulges and inner disks of spirals using absorption-line strengths. These measurements can provide the critical tests needed to understand the basic mechanisms driving bulge formation.

2. The stellar populations of spiral bulges

2.1. Sample and observations

We have selected a sample of 91 southern face-on spirals, ranging in type from S0/a to Sdm, barred and unbarred, from the ESO (B) survey. These spirals are not interacting, have major axes larger than $3'$, are within 4000 km s$^{-1}$ and are located at $|b| > 20^\circ$. The observations have been made using the long-slit Boller & Chivens spectrograph at Las Campanas Observatory in the blue, giving $\approx 2$ Å ($\sigma_{\text{inst}} \approx 35$ km s$^{-1}$) resolution in the 4000–5200 Å region. This spectral range covers portions of both the Lick/IDS (Burstein et al. 1984; Worthey et al. 1994; Trager et al. 1998a) and Rose (1985, 1994) absorption-line strength systems. To date, ten (primarily unbarred) spirals have been observed, most along both major and minor axes, and data from four have been processed. Line-strength profiles for these four galaxies have been calibrated onto the Lick/IDS system using stellar observations in common with Jones (1996), and velocity dispersion profiles and rotation curves have been derived following the Fourier-quotient procedure described by González (1993).

2.2. The Mg–$\sigma$ relation

As described above, bulge-first formation mechanisms find support in the observation that bulges in galaxies as late as Sc fall along the same Mg$_2$–$\sigma_0$ relation as early-type galaxies (Jablonka et al. 1996; Idiart et al. 1996), suggesting the existence of a mass-metallicity relation in spirals and a narrow spread in ages at fixed $\sigma_0$. We confirm these observational results: our bulges fall on the Mgb–$\sigma_0$ relation defined by early-type galaxies (our observations do not cover the red sideband of the broad Mg$_2$ index; see data in Trager et al. 1998a). However, the Mg–$\sigma$ relation is inherently degenerate to compensating variations in metallicity and age in old stellar populations—large age spreads can exist if there is a complementary age-metallicity relation (Worthey, Trager & Faber 1996; Trager 1997). This intrinsic age-metallicity degeneracy in Mgb and Mg$_2$ (and other metal lines and broadband colors) prevents the Mg–$\sigma$ relation from being an effective stellar population age discriminator. More sophisticated techniques are obviously necessary to distinguish between bulge formation mechanisms.

2.3. Balmer-metal line diagrams

There is a way to break the age-metallicity degeneracy—Balmer lines are more age-sensitive than metal-line indices (with the possible exception of the G band; Worthey 1994). In the absence of of nebular emission or large numbers of blue horizontal branch stars or blue stragglers, Balmer-line strengths reflect light-weighted mean turnoff temperature of the composite stellar population—i.e., the mean age of the population. Balmer lines do have some intrinsic metal dependence, however, so a clean separation of age and metallicity effects requires diagnostic diagrams combining Balmer line and metal line strengths. Figure 1 presents such diagrams for the first four galaxies analyzed in our sample.
Figure 1. Balmer–metal-line diagrams for two Sa–Sb spiral bulges (NGC 2775 and NGC 3054, left panels) and two Sc bulges (IC 438 and NGC 1637, right panels). The Balmer line index $H\gamma_A$ is a sensitive measure of the presence of intermediate-age (1–10 Gyr) stars in an old population. The metal-line index $C_24668$ is a sensitive measure of the bulk metallicity of an old population. Although both indices are slightly sensitive to both age and metallicity, used together they can effectively measure the mean age and metallicity in an old stellar population (Worthey 1994; Worthey & Ottaviani 1997; Trager et al., 1998). Points are coded by the axis along which the slit was placed, and grow smaller going out from the center. Closed symbols are as observed; the open symbols are an attempt to correct for the emission fill-in in the $H\gamma_A$ index using an optimized stellar template (cf. González 1993). Lines represent models of Worthey (1994) and Worthey & Ottaviani (1997): solid lines are contours of constant age and dotted lines are contours of constant metallicity. The Sa/Sb bulges on the left are clearly quite old (10–15 Gyr) and metal-rich (metallicities as high or higher than solar) and are older than their disks by at least a few Gyr. In contrast, the Sc bulges seem younger than the Sa–Sb bulges (< 10 Gyr), and the bulge of NGC 1637 is nearly as young as its disk. Both Sc bulges are also slightly metal-poor (metallicities less than solar), suggesting that a mass-metallicity relation may exist for spiral bulges, as suggested by the Mg–$\sigma$ relation.

The Balmer–metal-line diagrams for large bulges (Sab–Sbc, $\sigma_0 > 100$ km s$^{-1}$) suggest that the bulges of these early-type spirals are consistent with having old, metal-rich stellar populations, as seen in our own galaxy ($t > 10$ Gyr, $[C/H] > 0$; e.g., McWilliam & Rich 1994; Bruzual et al. 1997). These bulges are also older than their inner disks by several Gyr, suggesting that these bulges formed early on in the galaxies’ histories, and that bulge-first formation is a likely scenario for these galaxies.

On the other hand, small bulges (Sc, $\sigma_0 < 100$ km s$^{-1}$) seem to have younger and more metal-poor populations ($t < 10$ Gyr, $[C/H] \leq 0$), and at least in some galaxies (NGC 1637), the bulge and inner disk are roughly the same age. Such an observation provides strong support for a common origin of bulge and disk material—that is, for a disk-first formation scenario. However, contamination from emission is difficult to remove, separation of bulge and disk light has not yet been attempted, and small amounts of young or intermediate-age populations can significantly increase Balmer-line strengths (Trager et al. 1998b). In these late-type, star-forming, small-bulged galaxies, such effects may obscure truly old bulge populations.
3. Conclusions

The initial indications are that large bulges are genuinely old, metal-rich systems, as expected from our own galactic bulge. The stellar populations of small bulges appear to be younger and more metal-poor than the large bulges, but contamination from emission lines and disk light make these conclusions uncertain for the moment. If these results stand with more data and more extended analysis, we may find that bulges may have more than one formation mechanism—or even more than one mechanism may occur in a single galaxy (Rix, this meeting).

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