Formation and Evolution of Galaxy Bulges
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Symposium summary: dynamics

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Abstract. Pseudobulges form from unstable disks, while classical bulges form in violent episodes of star formation when a merger sweeps cold gas to a galactic centre. It seems unlikely that smashed disks contribute much to classical bulges. During mergers central black holes make cusps shallower and inflate kinematically decoupled cores. The abundance of galaxies with no detected classical bulge can perhaps be understood if galaxies exchange gas with the IGM more freely than is often supposed.

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1. Bulges, pseudo and otherwise

It is now clear that bulges fall into two classes: “classical bulges” are elliptical galaxies that happen to possess conspicuous disks, while “pseudobulges” are complex structures that have formed from disks.

A pseudobulge forms when a disk develops a strong bar: within the bar orbits become vertically unstable, causing the bar to buckle† (Athanassoula). Meanwhile gas from within the bar’s corotation radius is rapidly driven inwards. If there is a strong inner Lindblad resonance (ILR), the gas accumulates in a small, nearly round disk. Stars that form in this disk are likely to cause the overall surface-brightness profile of the gas to rise well above the exponential that fits the profile of the outer disk, and the inner disk will be considered to be part of the bulge regardless of its vertical thickness (Kormendy). Thus even though they are formed in a single fairly short-lived event, pseudobulges are geometrically complex structures, in which a bar that is thick at intermediate radii and thin near its edge may have a nearly round, flat disk at its centre.

If gas infall makes the disk that forms inside the ILR sufficiently massive, it will itself become bar unstable, and the process of pseudobulge formation will repeat itself on a lengthscale that is an order-of-magnitude smaller than that of the main pseudobulge.

If there is no ILR, or it is weak, gas will stream right in to the centre of the galaxy (Maciejewski).

1.1. *Kids on the block*

It has recently been shown that the Galactic disk is barred at radii slightly larger than the extent of the barred bulge (Mahoney). This finding chimes nicely with what is found in simulations of bar buckling (Athanassoula).

The bulge of the Milky Way is clearly old, yet at its velociy dispersion the bulges of external galaxies are generally found to be “young” (Thomas). As Minnitti pointed out, when there is a conflict between data for the Milky Way and external galaxies, experience teaches that the problem usually lies with our interpretation of the much sparser data for external galaxies. Probably external bulges are being deemed young because they contain

† In this review (Bloggs) is shorthand for “Bloggs, this volume and references therein.”

a minority of young stars, which leave a clear imprint on the aggregate spectrum. The majority of the stars are probably as old as most stars in the Milky Way's bulge. It would be good to know for sure whether this presumption is correct.

There has been some confusion about the status of the bulge of M31: the extent to which the $R^{1/4}$ law fits its surface brightness profile suggests that it is a classical bulge, while classification as a pseudobulge is suggested by its triaxiality and the kinematics of the inner disk, which suggest that it forms a rotating bar. Courteau argues that its Sersic index is significantly less than 4, so M31 is an example of an Sb galaxy with a pseuduo-bulge; none of the disk galaxies in the Local Group sports a classical bulge.

2. Classical bulges

The SAURON survey (Emsellem) has yielded rich insights into the internal dynamics of classical bulges, which are are either (a) cuspy, disky, axisymmetric, rotating or (b) cored, boxy, triaxial, negligibly rotating. The dynamical importance of rotation decreases with increasing luminosity. In fast rotators KDCs are much smaller than in slow rotators. In fast rotators, pressure anisotropy increases alongside v/σ, so the galaxies are jointly flattened by rotation and anisotropy.

In merger simulations, gas drives remnants towards axisymmetry (Naab), consistent with the finding of SAURON that substantial misalignment of kinematic and photometric axes is only seen in slow rotators, which tend to have cored surface-brightness profiles (Emsellem). In gas-poor mergers, the dynamical importance of rotation for the remnant is higher when the mass ratio of the progenitors is large than when it is small (Naab). Boxy, triaxial system cannot be formed by merging two disk galaxies, so these systems presumably form when bulge-dominated galaxies merge.

The widespread occurrence of shells or ripples in the luminosity profiles of giant ellipticals suggests that disk wrecking is a significant process in galaxy formation. A key question is the extent to which wrecked disks rather than in situ star formation dominate classical bulges.

Several arguments make it doubtful that classical bulges are made of wrecked disks:

- The phase-space density at the centres of cuspy ellipticals is too high to be formed by dissipationless disk wrecking (Ostriker 1980).
- Simulated mergers of disk galaxies yield remnants with $n_{\rm Sersic} < 4$ that show an insufficiently strong connection between boxiness and low v/σ (Naab).
- Disks form stars slowly, so have solar α/Fe rather than the enhanced values observed in all classical bulges (Arimoto), and it is hard for a remant of a disk merger to be as metal-rich as a luminous elliptical galaxy (Naab).
- The correlation between central black-hole mass and bulge mass suggests a common origin of black holes and bulges, while black holes must owe essentially all their growth to gas accretion.

When late-type galaxies merge, their disks must largely fade into a stellar halo, while gas driven from the disks to the centre of the remnant forms a bulge in a massive starburst. When a progenitor of a merger has a substantial bulge, this contributes to the bulge of the remnant. Stellar-dynamical processes, especially "core scouring" by the inspiralling central black holes of the progenitors, cause the central slope of the density profile of the remnant to be flatter than that of the progenitors (Milosavljevic & Merritt 2001). If gas is available to generate a central starburst, the profile can be restored to its original steepness by young stars and a cuspy bulge is formed. Otherwise the remnant is cored. Gas to re-sharpen the cusp may be unavailable because it is evaporated by an ambient virial-temperature corona (Nipoti & Binney 2007).

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In the SAURON survey, kinemantically decoupled cores (KDCs) are found to be more extended in cored systems than in cusped ones (Emsellem). This finding suggests that KDCs form only when cold gas is present during a merger; the KDCs of cored galaxies were inherited from progenitors, and during the merger were distended by tidal shocks from other KDCs and the black holes.

2.1. *Relation to central black holes*

Bars within bars are common (Schinnerer) and provide a natural mechanism for transporting gas from 10 kpc to near the black hole since sub-bars will form at an ILR whenever enough material accumulates to be self-gravitating. Simulations of the dynamics of selgravitating gas disks suggest that fragmentation does not stop non-axisymmetry of the potential driving significant quantities of cold gas inwards (Escala). Thus when cold gas is available during a merger, rapid black-hole accretion is to be expected, and we should not be surprised by the correlation between the cosmic densities of quasars and star formation.

Several attempts have been made to interpret the correlation the mass $M_\bullet$ of the central black hole and bulge velocity dispersion or luminosity in terms of feedback from accretion onto black holes (King). Although I am a long-standing propagandist for the importance of AGN feedback for the overall galaxy-formation process (Binney 2004), I do not see the necessity of invoking it to explain the correlations with $M_\bullet$: rapid accretion onto the black hole and star formation both depend on the ready availability of dense, cold gas at the centre of the galaxy. They both proceed at rates that scale with gas availability until such time as the gas supply is exhausted, when they both cease. Energy released by young stars and the black hole will together remove cold gas, but such feedback need play no role in establishing the correlation between bulge properties and $M_\bullet$.

2.2. *The challenge to ΛCDM*

In ΛCDM all massive dark-matter (DM) halos are remnants of mergers of objects, which were themselves remnants of earlier mergers. If early disks are gas-rich, mergers involving them should drive lots of gas to the centres of the remnants, endowing these systems with luminous bulges that will be passed on to remnants that form later.

The cuspiness of DM halos ensures that a DM halo that falls into a more massive halo during a minor merger either retains its integrity and continues to orbit the host as a satellite, or, if it is more massive, spirals to the centre of its host, dragging its central stars with it. In the latter case the minor merger will contribute to the classical bulge, so if there is to be no contribution to the classical bulge, the infalling halo has to have a mass smaller than the host mass by of order the number of dynamical times that have ellapsed since infall. N-body simulations and extended Press-Schechter theory both imply that insignificant numbers of DM halos are formed exclusively from such extremely minor mergers. So we expect every massive DM halo to possess a substantial classical bulge (Steinmetz).

For these reasons the existence of luminous galaxies such as M101 that have little or no bulge has long posed a challenge for ΛCDM. If, as Kormendy told us, *no* late-type galaxy has a classical bulge, the challenge is made enormously harder: all significant progenitors of the dark halo of any late-type galaxies must somehow have avoided significant merger-driven star formation until the present halo was fully assembled and relaxed. How do we reconcile this requirement with the fact that dwarf spheroidals galaxies do form, and that mergers are observed to be associated with violent bursts of star formation?

A measure of wriggle room is provided by the likelihood that small classical bulges are buried within observed pseudobulges (Erwin). Determining how large these buried

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classical bulges are is clearly an important task for the future. However, in the main the invisibility of classical bulges in late-type galaxies must be explained by a combination of two effects: (a) early disks are not gas rich because gas is slow to come in from intergalactic space, and (b) feedback is very efficient in systems with shallow potential wells, so when cold gas reaches the centre, the first few stars to form blast the remaining gas back to intergalactic space.

2.3. *Nuclear clusters and bulges*

HST has shown that $\sim 75\%$ of late-type spirals have nuclear star clusters with luminosities $10^6 - 10^7\,M_\odot$ and radii of a few parsecs (van der Marel). These almost non-rotating clusters are in some ways related to globular clusters, but they do not have simple stellar populations and contain dark matter. It's tempting to think of these objects as nascent classical bulges, although this interpretation is probably incompatible with standard interpretations of the fundamental plane and the $(M_\bullet, M_{\rm bulge})$ relation.

3. Morphology–density relation

My personal highlight of the meeting was the presentation of conclusive evidence that S0 galaxies are indeed stripped spirals (Aragon-Salamanca). This idea has been in circulation at least since the 1977 Yale meeting, but has time and again eluded demonstration. It is deeply satisfying to have closure at last. By focusing on rotation velocity as the quantity that remains the same as a galaxy is stripped, it was shown that stripping causes galaxies to fade by a factor ~ 3 over a period $\sim 4\,$Gyr. This fading is consistent with population-synthesis models and the observed abundance of S0s as a function of redshift. It is also consistent with the higher specific frequency of globular clusters in S0 galaxies.

4. Significant absences

Models of galaxies in the SAURON survey show no evidence of dark matter. Those who model the Milky Way's bulge have difficulty diverting part of the overall mass budget set by the circular-speed curve from stars, which contribute to the microlensing optical depth and non-circular velocities of gas, to dark matter, which contributes to neither (Minnitti). Those who measure the patterns speeds of bars find no evidence that bars have been slowed by interaction with dark-matter halos (Corsini). ΛCDM predicts the presence of significant densities of dark matter even in bulges, and it is perplexing that we can find no manifestation of it.

ΛCDM predicts that more than half of baryons are in intergalactic space, yet we have spent a week discussing the formation and evolution of bulges with barely a mention of mass exchange between bulges and this vast reservoir. As I have indicated above, the dearth of classical bulges suggests that feedback is efficient and infall of gas is prolonged. In these circumstances further decisive progress with the problem in hand will be possible only with a correct understanding of the exchanges of mass between galaxies and the IGM.

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