Galaxy Evolution: Emerging Insights and Future Challenges
ASP Conference Series, Vol. XXX, 2009
S. Jogee, L. Hao, G. Blanc, I. Marinova, eds.

Secular evolution and the assembly of bulges

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Abstract. Bulges are of different types, morphologies and kinematics, from pseudo-bulges, close to disk properties (Sersic index, rotation fraction, flatenning), to classical de Vaucouleurs bulges, close to elliptical galaxies. Secular evolution and bar development can give rise to pseudo-bulges. To ensure prolonged secular evolution, gas flows are required along the galaxy life-time. There is growing evidence for cold gas accretion around spiral galaxies. This can explain the bar cycle of destruction and reformation, together with pseudo-bulge formation. However, bulges can also be formed through major mergers, minor mergers, and massive clumps early in the galaxy evolution. Bulge formation is so efficient that it is difficult to explain the presence of bulgeless galaxies today.

1. Secular evolution and bulges, gas flows

There are excellent recent reviews on secular evolution (Kormendy & Kennicutt 2004, Jogee 2006), and in particular the formation of bulges has been debated in detail last year in Oxford, with the IAU Symposium 245 on "Formation and Evolution of Bulges". Only more recent work will then be reviewed here.

A clear distinction is now well established between classical bulges and pseudo-bulges, from the luminosity distribution (Sersic index, flattening, color) and the kinematics. On the color-magnitude diagram, the pseudo-bulges, similar in properties to disks, are clearly on the blue cloud, while the classical bulges sit on the red sequence (Drory & Fisher 2007). There is a clear bimodality in Sersic index, with the pseudo-bulge peak at n=1-2, and the classical bulge peak at n=4 (Fisher & Drory 2008).

Gaseous haloes around galaxies

The secular evolution is fueled by external gas accretion, and there is now growing evidence of gas infalling on nearby spiral galaxies, although this gas is quite diffuse. One of the best example is the edge-on galaxy NGC891 (Fraternali et al 2007). HI gas is observed up to 20kpc above the plane, with its rotation decreasing with the altitude. Part of this gas could come from galactic fountain, but not all, since the angular momentum should then be conserved. Moreover, modelisation of the fountain effect predicts gas outflow (cf the non edge-on galaxy NGC 2403), while mostly inflow is observed, like for high velocity clouds in the Milky Way. Gaseous haloes require accretion of external gas (Fraternali & Binney 2006).

A recent review by Sancisi et al (2008) gathers many examples of extra-planar gas. Part of it is due to dwarf companions or tidal streams, but evidence is mounting for extragalactic inflow of gas due to cosmic accretion. This external

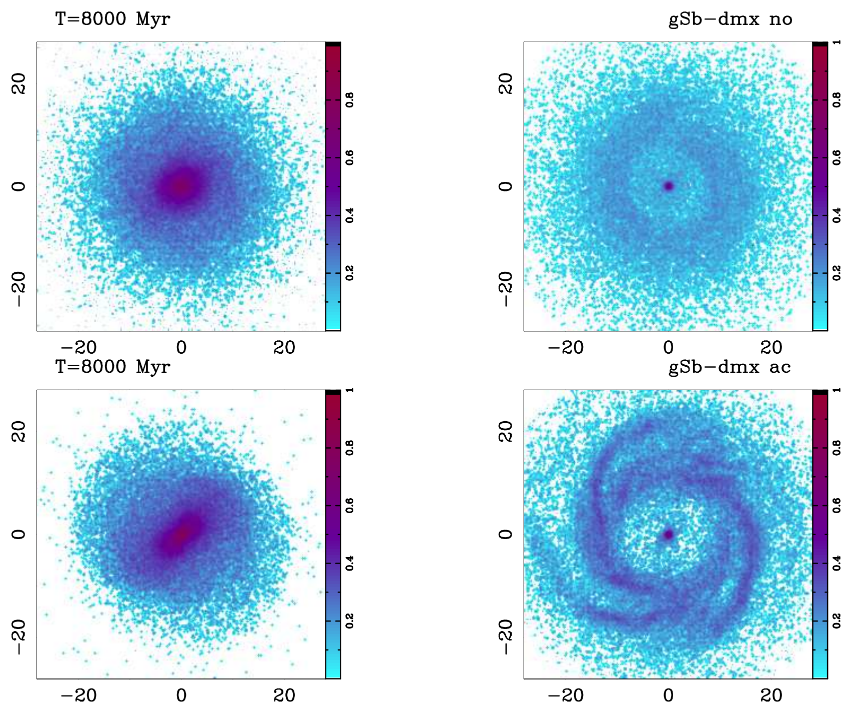

Figure 1. Comparison between two Sb galaxy models, without gas accretion (**top**) and with accretion (**bottom**). The Sb model is the maximum disk model (Combes 2008), the gas accretion rate is 5 $M_\odot$/yr, and the snapshot corresponds to T=8 Gyr. Note that a bar is maintained only in the case of gas accretion.

gas inflow produces lopsideness and fuels star formation. When the angular momentum of the accreted gas is close to perpendicular to that of the galaxy, polar rings can form. The simulation of this phenomenon by Brooks et al (2008) reveals how successively star formation is occuring in the inner equatorial disk, then in the outer polar disk. After 1.5 Gyr, the interaction between the two disks destroys the polar ring. The velocity curve is about the same in both equatorial and polar planes.

Relative role of gas accretion and mergers

In the standard hierarchical scenario, galaxies are thought to assemble their mass essentially through mergers. However, the gas accretion from cosmic filaments has been under-estimated. Analysis of a cosmological simulation with gas and star formation shows that most of the starbursts are due to smooth flows (Dekel et al 2008). Corresponding inflow rates are sufficient to assemble galaxy mass (10-100 $M_\odot$/yr).

2. Bar destruction, re-formation, role of gas

It is now well established that bar redistribution of mass and the vertical resonance can buiid secularly pseudo-bulges (e.g. Combes et al 1990). However, in a gaseous disk, not dominated by dark matter, the bar can quickly weaken and

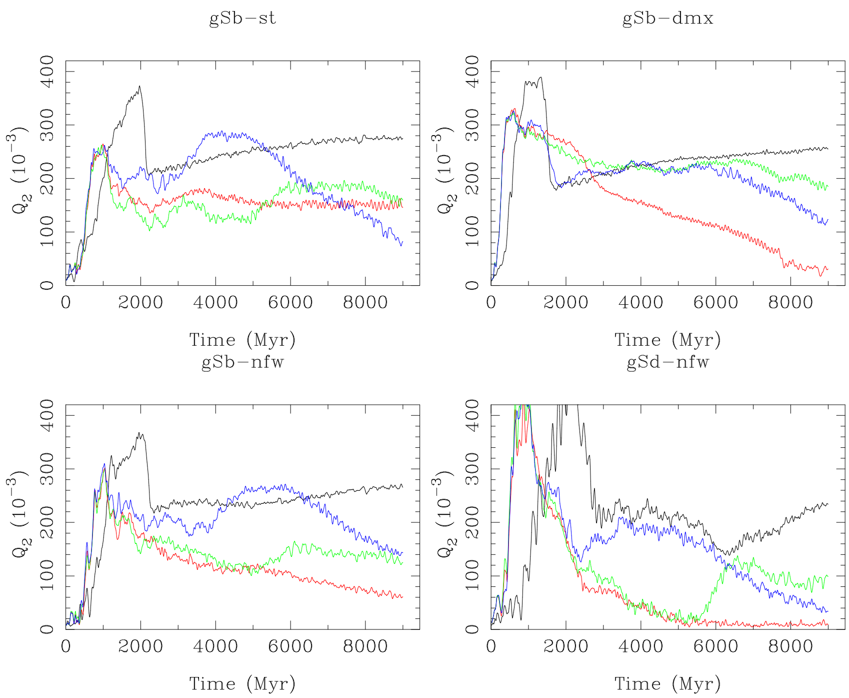

Figure 2. Evolution of bar strength, measured as the ratio Q_2 of the maximal $m = 2$ tangential force to the radial force, measured at a radius of 3.3kpc. The black curve corresponds to the purely stellar run, the red curve, to the spiral galaxy with initial gas, subject to star formation, but not replenished. These two curves are respectively the top and the bottom curves. The other curves corresponds to the models with gas accretion, 5 $M_\odot$/yr for the green one, and 5 $M_\odot$/yr for the blue one. There are 3 galaxy models corresponding to an Sb galaxy, with different mass ratios between disk and halo, and an Sd galaxy, with an NFW dark profile.

even be destroyed (cf Figure 1). With only 2% of the mass, gas infall is enough to transform a bar in a lens (Friedli 1994, Berentzen et al 1998, Bournaud & Combes 2002, Bournaud et al 2005). To pursue bulge formation, and explain the large frequency of bars, external gas accretion has to be invoked, in a self-regulated cycle: in a first phase, a bar forms through gravitational instability in a cold disk. The bar produces gas inflow, which itself weakens or destroys the bar, through angular momentum transfer to the bar. Then external gas accretion can replenish the disk, to turn back to the first phase.

Figure 2 illustrates such cycles, for different galaxy models, giant disks with different dark matter fractions, and different dark matter concentrations (Combes 2008). Although gas is provided at a constant inflow rate in the outer parts of the disks, it enters the galaxy disk by intermittence, and produces starbursts. Indeed, while the bar is strong, positive torques between corotation and OLR confine the gas outside OLR. Only when the bar weakens, the gas can replenish the disk, to make it unstable again to bar formation. Through these cycles, the pseudo-bulge can form, as shown in Figure 3.

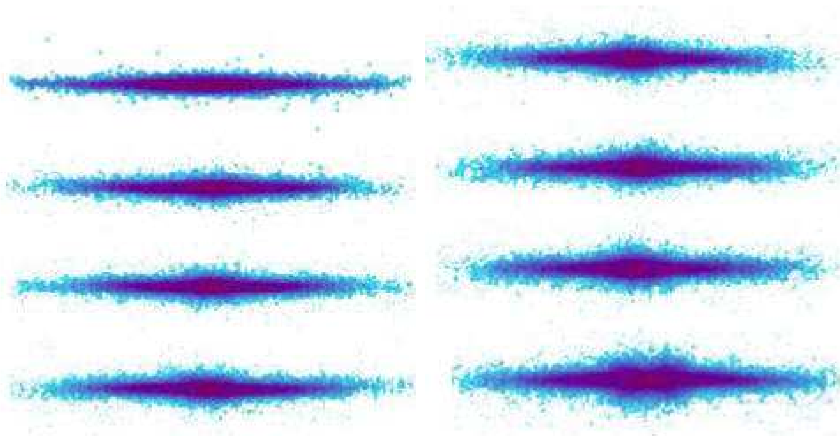

Figure 3. Formation of a peanut bulge, during bar formation, destruction, and reformation, for the standard Sb model. Time is running from top left to bottom left, then from top right to bottom right.

Formation in a cosmological context

In cosmological simulations, it is possible to take into account cosmic gas accretion more realistically. When spatial resolution is sufficient, it is possible to see bars form, destroy and reform (Heller et al 2007).

There is clearly in all these processes the influence of the adopted gas physics: bar formation is more easy with isothermal gas, while adiabatic gas heats and prevents disk instability. Star formation and feedback are then important keys to regulate the dynamics.

Angular momentum transfer with dark matter haloes

In presence of a massive dark halo, the angular momentum transfer is essentially towards the dark component, which helps to reform the bar. However, the bar destroys more quickly in presence of gas (Berentzen et al 2007). The weakening of the bar is then interpreted as due to the central mass concentration provided by the gas. It cannot be due to the vertical resonance, which is also weakened or suppressed in presence of large quantities of gas.

3. Bar and bulge statistics and high z evolution

The frequency of bars has been quantified on many samples, and in particular in the near infrared, where bars are easier to define (e.g. the OSU NIR sample, Eskrige et al 2002). In all samples, the main result is the paucity of weak bars (Marinova & Jogee 2007). Whatever the tool to measure bar strength, the number of strong bars is high at z=0 (Whyte et al 2002, Block et al 2002, Buta et al 2004).

Bar frequency with redshift

If at z=0 about 2/3 of galaxies are barred, with at least 30% strongly barred, the strong bars (ellipticity higher than 0.4) in the optical remain about 30% at redshift between 0.2 and 1 (Jogee et al 2004). At high z, however, results are more uncertain, because of the K-correction, and the lack of spatial resolution,

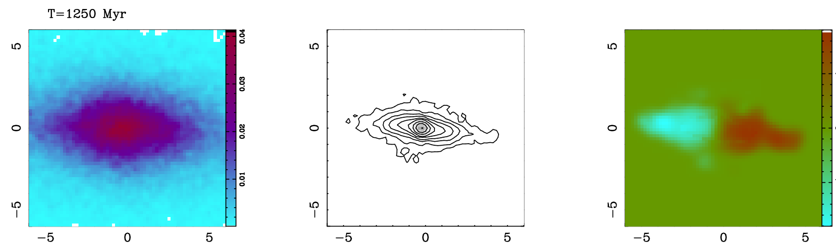

Figure 4. Result of the major merger of two equal-mass spiral galaxies, after 1250 Myr. Left is the stellar density, middle the gas density contours, and right the gas velocity field, where the wedge indicate the amplitude of the projected velocity in units of 100km/s. Not all mergers end up in an elliptical galaxy, but a significant pseudo-bulge is formed (Crocker et al 2008).

preventing to detect small bars. From a recent study of the COSMOS field, the bar fraction is found to decrease at high z (Sheth et al 2008). This is easy to interprete in terms of gas fraction: galaxy disks are more gas rich at high redshifts, and the gas inflow is destroying bars. The time spent in a barred phase is then expected to be smaller for galaxies at z $\sim$ 1.

B/T and n statistics

The bulge-to-total luminosity ratio (B/T) and the Sersic index n have been studied by several groups in near-infrared samples. A clear decrease of B/T and n has been found with the Hubble type, whatever the barred or unbarred character (Laurikainen et al 2007). In the OSU sample of 146 bright spirals in H-band, where 2/3 of galaxies are barred, 60% have $n < 2$, and B/T < 0.2, barred or not (Weinzirl, Jogee, Khochfar et al 2008). There is in addition a clear correlation between B/T and n.

This large observed fraction of low bulge galaxies is a constraint for models. In ΛCDM, a B/T<0.2 galaxy requires no merger since 10 Gyr (or last merger before $z > 2$). The predicted fraction of these low-bulge bright spiral is 15 times lower than observed (Weinzirl et al 2008). Most of these low-bulge bright spirals must be explained either by rare minor mergers or secular evolution, without mergers. With semi-analytical criteria, Koda et al (2007) propose a solution in terms of the tail of the distribution.

Frequency of bulge-less galaxies

Locally, about 2/3 or the bright spirals are bulgeless, or with a low-bulge (Kormendy & Fisher 2008, Weinzirl et al 2008). Some of the remaining have both a classical bulge and a pseudo-bulge, plus nuclear clusters (Böker et al 2002).

From the observed frequency of edge-on superthin galaxies, Kautsch et al (2006) estimate that 1/3 of galaxies are completely bulgeless. In the SDSS sample, 20% of bright spirals are bulgeless until z=0.03 (Barazza et al 2008). Disk-dominated galaxies are more barred than bulge-dominated ones. How can this be reconciled with the hierarchical scenario?

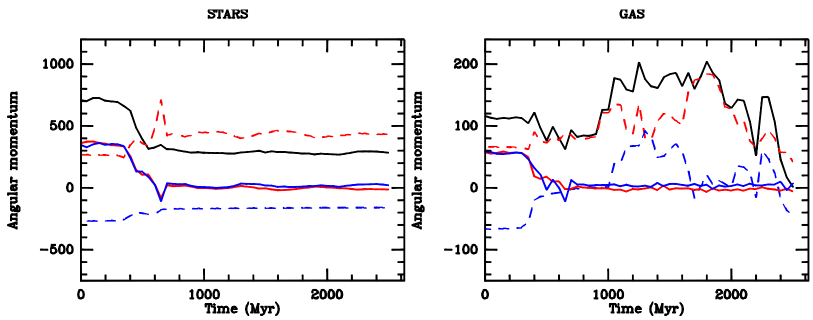

Figure 5. Angular momentum evolution of the stars (left) and gas (right) in the major merger simulation of Fig 4. The red curves correspond to the prograde galaxy, and the blue curves to the retrograde. The solid lines indicate the orbital angular momentum, while the dash lines indicate the internal spins. The scale is in units of 2.3 10^{11} $M_{\odot}$ kpc km/s (Crocker et al 2008).

4. Mergers and bulge formation scenarios

We can first remark that major mergers do not always lead to spheroids, or classical bulges, but sometimes also to pseudo-bulges. An extreme example is shown in Figure 4, the result of an equal mass merger, to reproduce the NGC 4550 system. This simulation is run with one disk prograde with respect to the relative orbit, and one disk retrograde, which leads to counter-rotation (e.g. Di Matteo et al 2007). In this system, the gas eventually settles in the prograde sense, in corotation with the prograde stellar disk, which is also the most perturbed in the interaction, thus ends up as a thicker disk. The angular momentum exchange between stars, gas and the orbit can be seen in Figure 5 (Crocker et al 2008). This major merger forms a bulge with low $n \sim 1-2$. This must also be the case for similar encounter geometries, i.e. for almost aligned or anti-aligned spins.

Scenarios of bulge formation

Although four different processes have been identified to form bulges, major mergers, minor mergers, bars and clumpy young galaxies, it is usually not easy to separate them in each galaxy, since they can occur successively.

In major mergers, the tidal trigger first forms strong bars in the partner galaxies, which drive the gas inward; this forms first a pseudobulge in each galaxy. Then the merger of the two galaxies could provide a classical bulge, according to the encounter geometry, which will co-exist with the pseudo ones.

Alternatively, after a classical bulge has formed in a system, subsequent gas accretion could re-form a disk and a bar, which drives the gas towards the center, and form a pseudobulge.

It is likely that most galaxy disks begin gas-rich, without central concentration, without bulge, and therefore are highly unstable to form clumpy galaxies at high z. Simulations show that there is rapid formation of an exponential disk and a bulge, through dynamical friction (Noguchi 1999, Bournaud et al 2007b). The evolution is slightly quicker than with spirals and bars. The rapid bulge formation is again a problem for the bulgeless galaxies today.

Clues from high z galaxies

Spheroids appear in place quite early (Conselice 2007). There is a deficit of disk galaxies at z=1. Could it be a bias of the observations with limited sensitivity? Or disky galaxies have formed only recently, and in poor environment? Big disks in rotation are however observed (Genzel et al 2008, Neichel et al 2008).

Massive bulges (B/T >0.2) and ellipticals have the same early formation, as shown by the GOODS study of 0.1 <z <1.2 galaxies (MacArthur et al 2008). Their star formation history (SFH) is compatible with a single early burst. There is however a degeneracy, the same SFH can be obtained, if the mass is assembled more recently from dry mergers.

Multiple minor mergers

The bulges formed by minor mergers are often the same as for major mergers, since they are more numerous. The issue is not the mass ratio of individual mergers, but the total mass accreted. As soon as a given spiral galaxy has accreted 30-40% of its initial mass, either in one event, or a series of small minor mergers, then the final result is likely to be an elliptical galaxy. Bournaud et al (2007a) have shown through simulations that 50 mergers of 50:1 mass ratio can easily form an elliptical, and this is certainly more frequent than a 1:1 merger.

5. Conclusion

Secular evolution and bars play a major role in pseudo-bulge formation, and this explains their presence in the blue sequence of galaxies. Since gas inflow weakens or destroy the bar, a galaxy can have several bar episodes, and each accumulates mass in the pseudo-bulge. Cold gas accretion, from cosmic filaments, can replenish galaxy disks, and reform bars. It is expected that bars were destroyed more frequently at high z, since galaxy disks contained more gas. This is in line with the observation of decreasing bar fraction at high z.

There are several scenarios for bulge formation, classical bulges through major mergers, but also a succession of minor mergers, clumps in young galaxies, coalescing in the center, due to dynamical friction, bars.. In most galaxies, there is coexistence of many processes and it is not easy to reconstruct the dynamical history of the bulge assembly. In any case, it is quite easy to form a bulge, in any galaxy environment, and it is a surprise to observe a large fraction of bulgeless galaxies. It is a challenge both for the hierarchical scenario, but also for the secular evolution. It is difficult in particular to find high-z precursors of these bulgeless galaxies. Have those disks formed recently?

Acknowledgments. Many thanks to Shardha Jogee and the organising committee to invite me at this stimulating conference.

References

Barazza F. D., Jogee, S., Marinova, I.: 2008 ApJ 675, 1194
Berentzen I., Heller, C. H., Shlosman, I., Fricke, K. J.: 1998, MNRAS 300, 49
Berentzen I., Shlosman, I., Martinez-Valpuesta, I., Heller, C.: 2007, ApJ 666, 189
Block, D. L., Bournaud, F., Combes, F., Puerari, I., Buta, R.: 2002 A&A 394, L35
Boeker T., Laine, S., van der Marel, R. P. et al.: 2002 AJ 123, 1389
Bournaud F., Combes F.: 2002, A&A 392, 83
Bournaud F., Combes F., Semelin B.: 2005, MNRAS 364, L18

Bournaud F., Jog C., Combes F.: 2007a, A&A 476, 1179
Bournaud F., Elmegreen, B. G., Elmegreen, D. M.: 2007b ApJ 670, 237
Brooks A. M., Governato, F., Quinn, T., Brook, C. B., Wadsley, J.: 2008, arXiv0812.0007
Buta, R., Laurikainen, E., Salo, H.: 2004 AJ 127, 279
Combes F., Debbasch F., Friedli D., Pfenniger D.: 1990, A&A 233, 82
Combes F.: 2008, in "Pattern Speeds along the Hubble Sequence", ed. E. Corsini and V. Debattista, arXiv:0811.0153
Conselice C.J.: 2008 IAUS 245, 429
Crocker, A.F., Jeong, H., Komugi, S., Combes, F., Bureau, M., Young, L. M., Yi, S.: 2008 arXiv0812.0178
Dekel, A., Birnboim, Y., Engel, G. et al. 2008, sub, astro-ph/0808.0 553
Di Matteo P., Combes F., Melchior A-L., Semelin B.: 2007: A&A 468, 61
Drory N., Fisher D. B.: 2007 ApJ 664, 64
Eskridge, P. B., Frogel, J. A., Pogge, R. W. et al.: 2002 ApJS 143, 73
Fisher D. B., Drory N.: 2008 AJ 136, 773
Fraternali F., Binney J.J.: 2006 MNRAS 366, 449
Fraternali F., Binney J.J., Oosterloo T., Sancisi R.: 2007 NewAR 51, 95
Friedli, D., 1994, in Mass-Transfer Induced Activity in Galaxies, Ed I. Shlosman, Cambridge University Press, p.268
Genzel R., Burkert, A., Bouché, N. et al.: 2008 ApJ 687, 59
Heller C.H., Shlosman, I., Athanassoula, E.: 2007 ApJ 657, L65
Jogee S., Barazza, F. D., Rix, H.-W. et al: 2004, ApJ 615, L105
Jogee S.: 2006, in Physics of Active Galactic Nuclei at all Scales, ed by D. Alloin, R. Johnson and P. Lira. Lecture Notes in Physics, Vol. 693
Kautsch S. J., Grebel, E. K., Barazza, F. D., Gallagher, J. S.: 2006, A&A 451, 1171
Koda, J., Milosavljevic, M., Shapiro, P. R.: 2007 arXiv0711.3014
Kormendy J., Kennicutt R.C.: 2004 ARAA 42, 603
Kormendy J., Fisher D.B.: 2008 ASPC 396, 297
Laurikainen E., Salo, H., Buta, R., Knapen, J. H.: 2007 MNRAS 381, 401
MacArthur L. A., Ellis, R. S., Treu, T., et al.: 2008, ApJ 680, 70
Marinova I., Jogee S.: 2007 ApJ 659, 1176
Neichel B., Hammer, F., Puech, M. et al: 2008 A&A 484, 159
Noguchi M.: 1999, ApJ 514, 77
Sancisi R., Fraternali, F., Oosterloo, T., van der Hulst, T.: 2008,A&ARv 15, 189
Sheth K., Elmegreen, D. M., Elmegreen, B. G. et al: 2008 ApJ 675, 1141
Whyte, L. F., Abraham, R. G., Merrifield, M. R. et al.: 2002, MNRAS 336, 1281
Weinzirl T., Jogee S., Khochfar S. et al 2008 arXiv0807.0040