On the Formation of Bulges and Elliptical Galaxies in the Cosmological Context

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Abstract. We study the formation of hot spheroidal systems within the frame of a scenario where galaxy formation and evolution is related to the gentle mass aggregation history and primordial angular momentum of protogalaxies, both defined by the cosmological initial conditions. We explore two cases: (1) the hot spheroidal system forms from the dynamical instabilities of the stellar disks, and (2) the spheroidal systems are formed during the dissipative collapse of the gas before falling to the disk in centrifugal equilibrium. In the former case a good agreement with observations for late type galaxies is found. In the second case, contrary to recent claims, we find that the tidal stability criterion is not easily reached. The gas that dissipatively collapses within the dark matter halos should be very clumpy, and the clumps very dense, in order to avoid the tidal destruction of the star formation unities.

1. Introduction

Galaxy formation and star formation (SF) are two related fundamental problems of contemporary astrophysics and cosmology. Crucial questions on these topics are: where, when, and how did stars form?; how the stellar systems did evolve?; which is the origin of the Hubble sequence? In the present-day universe almost all stars are located either in rotationally supported disks or in pressure supported spheroids. The stars could have been formed into these systems through several mechanisms:

(A) DISKS: that stars form in disks is a more or less well understood process, and actually is an ongoing observable phenomenon. The SF can be induced in the thin gaseous disk by gravitational instabilities and it may be self-regulated by an energy balance in the ISM along the vertical structure of the disk (e.g., Firmani & Tutukov 1992, 1994; Firmani, Hernández, & Gallagher 1996; Firmani, Avila-Reese, & Hernández 1997). Once the stellar disks have been formed, there are two main ways to partially or totally transform them into dynamically hot spheroidal systems: (A1) by internal dynamical instabilities (for example bars) in the stellar disks, and (A2) by external interactions between disks. In the former case it is expected the formation of bulge-like systems tightly connected to the properties of the disks (the secular mechanism, e.g., Norman,
Sellwood, & Hassan 1996 and the references therein), while in the second case
the interaction, in particular if it is strong (merger), leads to the destruction of
the disk, and to the formation of a pressure supported systems (e.g., Hernquist
1993). Nevertheless, these systems are not enough dense as the elliptical galaxies
(EGs) are. (A3) If the dynamical instabilities or the mergers occur when the
disks are still plenty of gas, then further gas concentration and subsequent bursts
of SF are possible. Dense hot spherical systems are expected to be formed in
these cases.

(B) HALO: Disk systems form because the protogalaxies have some initial
angular momentum and the gas concentrates until the centrifugal force equals
the attractive gravitational force. However, it is possible that the collapsing
gas transform into stars before to reach the centrifugal equilibrium. (B1) Gas
thermal instabilities before or during the dissipative collapse may produce pop-
ulation III stars (Lin & Murray 1992) and/or globular clusters (the stellar halo).
(B2) The low angular momentum gas clouds may attain high densities after a
considerable dissipative collapse in such a way that the SF is triggered; further
the SF can run by a self-regulated mechanism (e.g., Burkert 1994).

Since the galactic morphological type strongly depends on the environment,
it is also possible that physical mechanisms related to the environment like the
tidal stripping, the galaxy harassment, etc., are able to change the morphology
of galaxies.

The real understanding of the galaxy formation phenomenon can not be ac-
complished without considering the cosmological context. The inflationary CDM
models together with the gravitational paradigm predict that cosmic structures
form through a hierarchical mass aggregation process. Within the hierarchical
clustering picture two general scenarios of galaxy formation can be formulated:
1) the merging scenario, where the main properties of galaxies are deter-
mined by the merger histories of their dark matter (DM) halos (see Baugh 1998
in the present volume, and the references therein), and 2) the extended col-
lapse scenario, where the properties of galaxies are mainly established by the
combination of three factors defined by the initial cosmological conditions: the
mass, the hierarchical mass aggregation history (MAH), and the primordial an-
gular momentum (Firmani et al. 1997, Avila-Reese 1998; Firmani & Avila-Reese
1998; see also Gunn 1982, 1987; Ryden & Gunn 1987). Here we shall explore
the problem of bulge and elliptical galaxy formation in the light of the second
scenario, for which the mechanisms (A1) and (B2) are adequate.

2. Disk galaxies and the secular bulge formation mechanism

In the extended collapse scenario the disks form inside-out with a gas accretion
rate dictated by the hierarchical mass aggregation process. The SF is modeled as
was described above (see point (A)). The secular mechanism of bulge formation
(the (A1) case) was followed through a simple physical formulation: all the stars
localized in the gravitational unstable regions according to the Toomre criterion
are transferred to a spherical component. This formulation is in agreement with
the results of detailed simulations which show that the dynamical instabilities
in the disks produce bars which then dissolve forming dynamically hot regions
(Norman et al. 1996 and the references therein).
Figure 1. Evolution of the bulge-to-total luminosity ratio for models with the average MAHs, $\lambda = 0.05$ and for the SCDM, $\sigma_8 = 0.6$ model. $\Delta \log(b/t) \equiv \log(b/t)(z) - \log(b/t)(0)$. The thick segment corresponds to the slope inferred from the observational data presented in Lilly et al. 1998. The more massive systems form their bulges earlier than the less massive ones.

Using the standard CDM model normalized to $\sigma_8 = 0.6$ as a representative case, we obtain that as the model disks are redder and with higher surface brightnesses, their gas fractions are lower and the bulge-to-disk (b/d) ratios are larger, i.e. the models follow the correlations of the Hubble sequence (Firmani & Avila-Reese 1998). The b/d ratios strongly correlates with the central surface brightnesses $\mu_{B_0}$ and do not correlate with the color indexes B-V (the models follow a biparametrical sequence where $\mu_{B_0}$ and B-V are the two parameters). The predicted b/d ratios for different masses, MAHs, spin parameters $\lambda$, and realistic cosmological models agree with the ratios derived from the observations for disk galaxies (de Jong 1996). The b/d ratio is mainly determined by $\lambda$: more concentrated self-gravitating disks imply more dynamical instabilities and therefore larger bulges. An interesting prediction of the secular mechanism applied here is that the more massive systems form their bulges earlier than the less massive ones (Figure 1).

For extreme cases (very low $\lambda$'s or strong angular momentum transference) the disks result very concentrated and completely self-gravitating (the (A3) case). Although our models are not able to follow the dynamical evolution in these particular cases, it is much probable that the disks will considerable thicken or even completely destroy giving rise to hot spheroidal systems whose properties could resemble those of the disky EGs. In this sense the initial angular momentum and/or the ability of the protogalaxy to transfer angular momentum (the last is related to the clumpyness, the environment and the rapidity of the collapse of the protogalaxies) could be key factors which determine the sequence of Disk-SO-Elliptical galaxies proposed for example in Kormendy & Bender (1996). It is important to emphasize that, according to our models where the disks build-up within the evolving cosmological DM halos and where the gravitational pull of the gas is calculated, the circular velocities of the system become
Figure 2. Rotation curve decomposition of a galaxy model of $5 \times 10^{11} M_{\odot}$ with the average MAH and $\lambda = 0.03$, and for the $\Lambda$CDM model (thin lines). The solid line is the total rotation curve of the same model but when 62% of the gas was transformed into stars in the halo before to fall to the disk.

more and more concentrated (steeply increasing, and after the maximum, decrease) as the b/d ratio increases. In Figure 2 it is shown the rotation velocity of a galactic system with a low spin parameter, $\lambda = 0.03$ (thin solid line; the b/d ratio in this case is 0.19). How are the gravitational potentials of EGs? Rix et al. (1997) have intended to explore this difficult question and they concluded that for the only EG they studied (NGC2434) the circular velocity profile is flat. If this is confirmed for other EGs, then the secular disk instability mechanism is not adequate to predict the formation of EGs.

The simplified scheme of secular bulge formation applied to our disk galaxy evolutionary models has shown to be predictive, at least for late type galaxies. According to the secular mechanism, the properties (color, scale lengths, etc.) of the spheroids are closely associated to those of the disks. For late type galaxies the observations indeed are in agreement with these behaviors (Peletier & Balcells 1996; de Jong 1996; Courteau et al. 1997). However, for early type galaxies (<Sb) bulges and disks seem to have formed separately (e.g., Wyse, Gilmore, & Franx 1998). Therefore alternative scenarios should be explored in order to explain early type galaxies.

3. The dissipative collapse mechanism

As was mentioned in the introduction the collapsing gas within the DM halos can be transformed into stars before to reach the centrifugal equilibrium. The first condition the gas should obey for this is the so called Roche criterion: the gas clouds should be enough dense to avoid their destruction by the global tidal forces. In a recent work Mao & Mo (1998), using the DM halo profiles predicted in the cosmological simulations (Navarro, Frenk, & White 1997) and
the $\lambda$–distribution obtained in analytical and numerical studies, calculated the baryon matter fraction that satisfies the inequality

$$\rho_{\text{gas}}(r) > 3\rho_{\text{tot}}(< r)$$

that roughly approximates the Roche criterion. Assuming that this gas fraction is transformed into a spheroidal stellar system, Mao & Mo concluded that the predicted $b/d$ ratios match the observations. We have carried out a more detailed calculation which implies (i) the overall gravitational collapse and virialization of the primordial density fluctuations (the most probable cases are in agreement with the Navarro et al. halo profiles; see Avila-Reese, Firmani, & Hernández 1998), (ii) the dissipative collapse of the gas and its gravitational pull on the DM halo, and (iii) the formation of a rotationally supported disk within the evolving halo. We find that for the $\lambda$–distribution used by Mao & Mo (1998) and for the realistic cosmological models, the tidal stability criterion (1) is almost never reached. This discrepancy with the simplified analysis of Mo & Mao is mainly due to the evolutionary effects and the gravitational pull of the gas over the DM halo, both considered in our case.

A more correct expression than (1) for the Roche criterion is:

$$\rho_{\text{gas}}(r) > 2\rho_{\text{tot}}(< r) * \left(1 - \frac{1}{3} \frac{d\ln M(r)}{d\ln r}\right)$$

In this case some fraction of the gas satisfies (2). For example, for the $\Lambda$CDM$_{0.3}$, $\Omega_m = 0.3$, $h=0.65$ model and for the average MAHs this fraction goes from 4.0% to 0.9 % for $\lambda = 0.03$ and $\lambda = 0.085$, respectively. The range of variation of this fraction is much less with the MAHs. Only for extreme cases of a very low $\lambda$ and a very fast MAH, the gas fraction that satisfies (2) attain values of 10-20%. In conclusion our models show that for the uniformly falling gas into the center of the evolving cosmological DM halos the tidal stability Roche criterion is not easily obeyed. To avoid the tidal destruction of the SF unities the gas should have a clumpy distribution and much of the clumps should be much denser than the average gas density. The dense clumps may originate due to the non-homology of the collapse and/or due to the large scale gas streams that collide in the center forming highly gas compressed regions.

To obtain a considerable fraction ($> 50\%$) of gas that satisfies (2) the gas density should be incremented by factors larger than 20. In these cases (2) is widely satisfied since large redshifts up to $z\approx 2 - 3$ (for the $\Lambda$CDM$_{0.3}$ model). At these epochs the fraction of collapsing gas into the DM halos that obeys the Roche criterion (2) is 0.8-1.0. If all this gas is transformed into stars then at $z\approx 2 - 3$ the bulge-to-total ratios of the model galaxies are near to one. In the central regions of the galaxy clusters, where high density peaks complete their collapse early, these ratios may be maintained until the present epoch.

It is interesting to note that for these cases since the low angular momentum gas is not allowed to fall until its centrifugal equilibrium radius, but it is transformed into stars before, the resulting rotation curves are flatter than in the cases all the gas is allowed to fall into a disk in centrifugal equilibrium. In Figure 2 it is shown the rotation curve (thick solid line) of the same model corresponding to the thin line, but where 62% of the gas has been transformed into stars in the halo.
3.1. The star formation regime

In analogy with the disk, one can expect that SF in the halo is self-regulated by some mechanism once it was triggered. In the case of the disk this self-regulation mechanism is commonly given by an energy balance in the ISM (e.g., Firmani et al. 1996). The resulting SF timescale is \( t_{SF} = \frac{2\varepsilon v_g}{v_g t_{diss}} \), where \( \varepsilon \) and \( v_g \) are constants related to the negative feedback of the supernova energy injection, \( v_g \) is the gas velocity dispersion, and \( t_{diss} \) is the time scale of the gas (turbulent) energy dissipation (see Firmani et al. 1996). Since \( v_g \) in the disks is relatively small, \( \sim 6 - 10 \) km/s, we obtain typically \( t_{SF} \approx 100t_{diss} \), i.e. the negative feedback dominates the SF timescales (inefficient SF). In the case of the halo the gas clouds are infalling typically with velocities of \( \sim 100 - 400 \) km/s (the virial velocities), therefore \( t_{SF} \approx 3 - 5t_{diss} \), i.e. the negative feedback is not too important, the SF is more efficient than in the disks. Since \( t_{SF} \) is now near \( t_{diss} \) and \( t_{diss} \), according to our model results, depends on the galaxy mass (virial velocity), then \( t_{SF} \) depends on mass. Thus, the b/d ratio will depend on mass. It is probable that the physical conditions of the gas in the halo and in the disk are quite different in such a way that a direct analogy is not possible. The understanding of the SF regime in the halo remains as an open crucial theoretical question.

4. Conclusions

The main conclusions drawn from our models of formation of hot spheroidal systems within the frame of the cosmological extended collapse scenario are: (1) the secular mechanism of bulge formation is able to produce b/d ratios and correlations compatible with those observed in late type galaxies; for very low angular momentum protogalaxies the whole disks are dynamically unstable and S0/disky elliptical galaxies may form, however, in these cases the circular velocities of the systems result strongly decreasing. (2) for the dissipative collapse model of EG formation we find that the density of the gas that uniformly falls to the center of the cosmological DM halos almost never is enough to obey the tidal stability (Roche) criterion; a very clumpy gas dissipative collapse should be evoked in order to form large hot spheroidal components. (3) If the SF regime in the dissipative collapse model is self-regulated by an energy balance in the ISM analogous to that of the disk, then a strong dependence of the b/d ratio on the galaxy mass is expected.

References

Avila-Reese, V. 1998, Ph.D. Thesis, UNAM (México)
Avila-Reese, V., Firmani, C., & Hernández, X. 1998, ApJ, v.505, (in press)
Burkert, A. 1994, Reviews in Modern Astronomy, v.7, p. 191
Courteau, S., de Jong, R.S., & Broeils, A.H. 1997, ApJ., 457, L73
de Jong, R.S., A&A, 313, 45
Firmani, C. & Avila-Reese, V. 1998, in preparation
Firmani, C., Avila-Reese, V., & Hernández, X. 1997, in “Dark and Visible Matter in Galaxies”, M. Persic and P. Salucci (eds.), ASP Conference Series, v.117, p.424
Firmani, C. & Tutukov, V. 1992, A&A, 264, 37
Firmani, C. & Tutukov, V. 1994, A&A, 288, 713
Firmani, C., Hernández, X., & Gallagher, J. 1996, A&A, 308, 403
Gunn, J.E. 1981, in “Astrophysical Cosmology”, M.S. Longair, G.V. Coyne, and H.A. Brück, (eds.) (Pont. Ac. Scientarium: Citta del Vaticano), 233.
Gunn, J.E., 1987 in “The Galaxy”, G.Gilmore and B. Carswell, (eds.), (Reidel Publishing Company), 413
Hernquist, L. 1993, in “The Environment and Evolution of Galaxies”, J.M.Shull and H.A. Thronson (eds.) (Kluwer Ac. Publishers), p.327
Kormendy, J. & Bender, R. 1996, ApJ, 464, 123
Lilly, S. et al. 1998, ApJ, 500, 75
Lin, D.N.C. & Murray, S.D. 1992, ApJ, 394, 523
Mao, S. & Mo, H.J. 1998, preprint (astro-ph/9805094)
Navarro, J.F., Frenk, C.S., & White, S.D.M. 1997, ApJ, 490, 493
Norman, C.A., Sellwood, J.A., & Hassan, H. 1996, ApJ, 462, 114
Peletier, R., & Balcells, M. 1996, AJ, 111, 2238
Rix, H.-W., et al. 1997, ApJ, 488, 702
Ryden, B.S., & Gunn, J.E. 1987, ApJ, 318, 15
Wyse, R.F.G., Gilmore, G., & Franx, M. 1997, ARA&A, 35, 637