Formation and Evolution of Galaxy Bulges
Proceedings IAU Symposium No. 245, 2007
M. Bureau, E. Athanassoula & B. Barbuy, eds.

doi:10.1017/S174392130801716X

How to form bulges/ellipticals in dark halos as fast as central black holes?

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Abstract. Gravity is nearly a universal constant in the cusp of an NFW galaxy halo. Inside this external field an isothermal gas sphere will collapse and trigger a starburst if above a critical central pressure. Thus formed spheroidal stellar systems have Sersic-profile and satisfy the Faber-Jackson relation. The process is consistent with observed starbursts. We also recover the $M_{BH} - \sigma_*$ relation, if the gas collapse is regulated or resisted by the feedback from radiation from the central BH.

Keywords. black hole physics – galaxies: formation – galaxies: starburst – galaxies: structure

1. Tight correlation of formation of black holes and bulges

The formation of central black holes (BHs) in galaxies is likely a rapid process since most quasars have already formed at redshift $z > 2$. The co-relation between the BH mass and the velocity dispersion of the spheroidal (bulge) component is so tight that it is hard to explain unless bulges form as fast as BHs to keep their growth neck-to-neck. While at the present day the BH accretion rate is completely decoupled from the bulge growth, it is possible that their growth was correlated during the violent feedbacks at high redshift. Indeed starburst activities peak at similar redshifts as quasars as a whole.

In two recent papers by Xu, Wu, & Zhao (2007) and Xu & Wu (2007), we propose that bulges can form by a rapid collapse due to radial instability of isothermal gas. This model has the nice feature of forming bulges before disks.

Here we iterate the key steps of the above scenario, but without invoking the gravothermal instability as in Xu *et al.* (2007). Instead we follow Elmegreen (1999) and find the equilibrium configurations of the maximum gas mass inside an external gravity. We also generalize the argument to a star-gas mixture to show we can form bulges with a reasonable profile. Assuming the rapid star bursts in the bulge are regulated by the accretion-driven wind of the central black hole, we derive the BH mass-stellar dispersion relation.

2. A universal constant gravity scale for dark halos

In the Cold Dark Matter (CDM) framework, baryons fall into the potential well of CDM, cool and condense into stars. Here we consider the properties of gas and stellar equilibrium in the external field of dark matter.

The background dark matter distribution is often described by the NFW density distribution for dark matter (Navarro, Frenk & White 1997), which has a density $\rho_{NFW} \approx \rho_s r_s / r$ inside a scale radius r_s. In the central region which concerns the galaxy bulge, we note *an interesting universal scale for the dark halo gravity*

$$g_{\rm DM}(r) = \frac{GM_{DM}(r)}{r^2} = 2\pi G\Pi \sim 10^{-10}\text{m sec}^{-2}\Xi, \qquad \Xi \sim 1 \tag{2.1}$$

where $\Pi = \rho_s r_s \sim 130 M_{\odot}\mathrm{pc}^{-2}\Xi$ is a column density and $\Xi(M_{vir}, z, c) \sim 1$ is a shallow function of the halo virial mass M_{vir}, the redshift, and the concentration c. In other words, the gas where formed the bulge was imbedded in a uniform external field from the dark matter potential. We can also define a dark matter central pressure P_{DM} for later use:

$$P_{DM} \equiv g_{DM}^2/(4\pi G) = g_{DM}\Pi/2 = \rho_{DM}(r) \cdot g_{DM} \cdot (r/2). \tag{2.2}$$

3. Maximum gas mass sustainable by halo gravity

In general for a gas and a stellar sphere imbedded in an external DM gravity, Consider imbedded in an external DM gravity an isothermal gas sphere $\rho(r)$ of sound speed σ, and an isotropic stellar sphere $\rho_*(r)$ of dispersion σ_* in quasi-static equilibrium, the potential at a given radius r is

$$\Phi = \int_0^r \left(g_{DM} + \frac{GM + GM_*}{r^2} \right) dr. \tag{3.1}$$

The equilibrium satisfies the equations

$$\left(g_{DM} + \frac{GM + GM_*}{r^2} \right) = -\frac{\sigma_1^2 d\ln[\sigma^2\rho(r)]}{dr} = -\sigma_*^2 \frac{d\ln[\sigma_*^2\rho_*(r)]}{dr}, \tag{3.2}$$

$$4\pi r^2 = \frac{dM(r)}{\rho(r)dr} = \frac{dM_*(r)}{\rho_*(r)dr}, \tag{3.3}$$

where we define $\sigma_1^2 \equiv (1+\Gamma)\sigma^2$. Here a position-independent feedback factor $\Gamma \gg 1$ is introduced because the radiation from the star burst and the accreting central black hole can generate an additional opacity-induced pressure $(\rho\sigma^2)\Gamma$ on the dusty gas sphere (but not the stellar sphere), countering the gravity.

First consider the stage where the stellar mass is negligible, so $M_* \ll M$. Rewrite the equations in term of the following dimensionless mass, radius and density,

$$m \equiv \frac{M}{\sigma_1^4 g_{DM}/G}, \qquad x(m) \equiv \frac{r}{\sigma_1^2/g_{DM}}, \qquad p(m) = \frac{\rho(M)\sigma_1^2}{g_{DM}^2(4\pi G)^{-1}}, \tag{3.4}$$

and express the rescaled gas mass m as the independent coordinate, the problem is recasted to solving the pair of dimensionless ODEs

$$-\frac{x^2 dp(m)}{dm} = 1 + \frac{m}{x(m)^2}, \qquad \frac{x^2 dx(m)}{dm} = \frac{1}{p(m)}. \tag{3.5}$$

For each value of $p(0)$, the gas density profile under the hydrostatic equilibrium can be totally determined with the following initial conditions at the center for the radius $x(0) = 0$ and the rescaled density

$$p_0 = p(0) = \frac{\rho_0\sigma_1^2}{P_{DM}}, \qquad P_{DM} \equiv \frac{g_{DM}^2}{4\pi G}, \tag{3.6}$$

where $p(0)/(1+\Gamma)$ equals the ratio of the gas central pressure $\rho_0\sigma^2$ vs the dark matter's pressure under self-gravity P_{DM}.

Computing the gas equilibrium for a range of core pressure p_0 (see figure 1), we find that the gas density generally falls montonically with radius or mass. All models have finite mass out to infinite radius where $\rho = 0$. This interesting behavior is due to the deep potential well of the external gravity, which makes the isothermal density drop exponentially with radius as $-\frac{\sigma_1^2}{g_{DM}} \ln \frac{\rho(M)}{\rho_0} \sim r(M)$, hence the mass converges quickly if neglecting self-gravity.

The finite mass of these gas spheres will give another interesting behavior. There is a critical core pressure

$$p_0 = \frac{\rho_0 \sigma_1^2}{P_{DM}} \approx 30 \tag{3.7}$$

above which the gas density $\rho(M)$ of a parcell of gas dM no longer increases monotonically with an increase of central pressure, and in fact the total mass will decrease with increasing p_0 after it reaches a maximum value

$$M_{max} \approx 4.3 \left(\frac{\sigma_1^4}{g_{DM} G} \right). \tag{3.8}$$

These limits on gas central pressure and total mass are related to the instability first discussed by Elmgreen (1999). Gas sphere above certain critical mass $M_{max} \propto \sigma_1^4$ or critical central gas density or pressure do not have stable solutions; adding tiny amount of gas would lead to collapse. It is interesting to speculate that the bulge formation originates from such a gas instability.

4. Post-starburst mass profile

Our models are also *generalizable* while gas is converting to stars. The simplest solution would be a model where *stars trace gas* radial distribution, so we have

$$\frac{\rho_*(r)}{\rho(r)} = \frac{M_*(r)}{M(r)} = \frac{f_*}{1-f_*}, \qquad \frac{\sigma_*^2}{\sigma^2} = 1 + \Gamma \gg 1, \tag{4.1}$$

where the position-independent factor $f_*(t)$ is the fraction of gas formed into stars at time t. Such a solution is possible if the feedback is regulated by star formation. Rescaling the gas-only solution, we obtain the stability criterion

$$\frac{\rho_0 \sigma^2}{(1-f_*)/(1+\Gamma)} = \frac{\rho_{*,0} \sigma_*^2}{f_*} \leqslant \frac{30 g_{DM}^2}{2\pi G}. \tag{4.2}$$

Gas can turn into stars quasi-staticly where maintaining the above equality at the critical density and mass. Such formed stellar system would have a total mass

$$M_*^\infty = \frac{4.3\sigma_*^4}{g_{DM} G} \sim 4 \times 10^{11} M_\odot \left(\frac{\sigma_*}{200\text{kms}^{-1}} \right)^4, \tag{4.3}$$

and a profile

$$\frac{M_*(r)}{M_*^\infty f_*(t)} = \int_0^y j(y)(4\pi y^2 dy), \qquad y = \frac{r}{\sigma_*^2 g_{DM}^{-1}}, \qquad j(y) \approx 0.64 y^{-1} \exp(-1.6 y^{1/1.2}), \tag{4.4}$$

where $j(y)$ is numerically fitted by a Sersic profile (of the volume density with a total mass unity). Integrating the density, we find the central surface density $I_*(0) f_*^{-1} \sim 2g_{DM}/G \sim 10\Pi \sim 1300 M_\odot \text{pc}^{-2}$ for these systems, independent of the initial gas dispersion σ and the feedback parameter Γ. Eventually $f_* = 1$ when the gas is exhausted by star formation, and we form a stellar system with a bulge-like density profile. Our model resembles real bulges in term of the central brightness $I_*(0)$ and the Faber-Jackson-like relation $M_*^\infty \sim \sigma_*^4$ between the total mass and stellar dispersion.

During the star burst (SB), the central Black Hole (BH) accretes. the SB and BH emit photons with a luminosity L_{SB+BH}, which diffuse out of the gas sphere while keeping the gas isothermal. The momentum deposite rate $\frac{2L_{SB+BH}}{c}$ of photons drives an overall

https://doi.org/10.1017/S174392130801716X Published online by Cambridge University Press

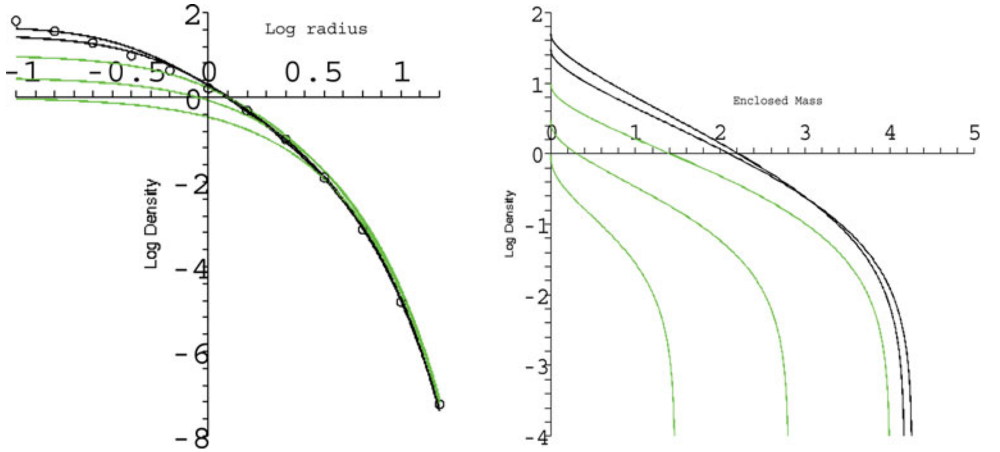

Figure 1. shows mass distribution of an isothermal gas sphere embedded in a NFW dark matter cusp of a uniform gravity $g_{DM} \sim 10^{-10}$m/sec^2 for models (from bottom to top) with increasing dimensionless central gas pressure $p_0 = 1, 3, 10$ (in solid green), and $p_0 = 30, 100$ (black dashed). Panel (a) shows the models in $\log p(m)$ vs $\log x(m)$ (rescaled density vs. rescaled radius $x(m) = \frac{r}{\sigma^2/g_{DM}}$). Note how the black curves are above the green curves at small radii, but dip below the green curves at large radii, a feature of reaching a maximum in total gas mass at the critical pressure ($p_0 = 30$). Also shown is a Sersic ($n = 1.2$) profile (red circles). Panel (b) shows $\ln p(m)$ (the logarithm of rescaled gas density or pressure, $p(m) = \frac{\rho(M)\sigma^2}{g_{DM}^2/(4\pi G)}$) as function of the rescaled enclosed gas mass $m = M/(\sigma^4/G/g_{DM})$, cf. eq. 3.4). Note the total gas mass m increases with p_0 until the critical value $p_0 \sim 30$, afterwards the mass decreases with central pressure.

feedback force acting on the gas, which can be computed by

$$\frac{2L_{SB+BH}}{c} = F(t) = \int_0^\infty d(4\pi r^2)(\rho\sigma^2)\Gamma \sim \frac{10(1-f_*)\Gamma}{1+\Gamma}\frac{\sigma_*^4}{G} \sim 2(1-f_*)M_*^\infty g_{DM} \quad (4.5)$$

insensitive to Γ if $\Gamma \gg 1$. The luminosity and force are maximum initially and die out as the star burst finishes. If the maximum luminosity at the onset of star burst is contributed fifty-fifty between the luminosity of the SB and the Eddington luminosity of the BH, then we obtain

$$\frac{M_{BH}}{10^8 M_\odot} = \frac{L_{SB}}{10^{13} L_\odot} = \left(\frac{\sigma_*}{200\mathrm{kms}^{-1}}\right)^4, \quad (4.6)$$

which agree with the observed scaling relations of the stellar dispersion σ_* with the BH mass and the star burst luminosity respectively. Assuming the usual SB efficiency of 0.001, the star formation time scale is $0.001 M_*^\infty c^2/L_{SB} \sim 0.04 H_0^{-1}$, comparable to the free-fall time scale ~ 0.1Gyr. The short time scales and high luminosity are consistent with the assumption of violent feedback $\Gamma \gg 1$.

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