A feedback compression star formation model and the black hole-bulge relations

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ABSTRACT

We present a "feedback compression" model to describe the galactic spheroid formation and its relation with the central nuclear activity. We suggest that the star formation itself can serve as the "positive feedback" in some extremely dense region to trigger the starburst. The star formation rate as well as the related stellar feedback-induced turbulence will be maximized under the regulation of the background dark halo's gravity. There is also stellar feedback acting inward to confine and obscure the central black hole (BH) till the BH grows sufficiently large to satisfy a balance condition between the accretion disk wind and the inward stellar feedback. The extremely vigorous star formation activity, the BH-bulge relations, the maximum velocity dispersion as well as the maximum BH mass are investigated based on such scenario, and are found to be consistent with observations.

Subject headings: black hole physics – galaxies: formation – galaxies: nuclei – galaxies: starburst – galaxies: structure

1. INTRODUCTION

Observations have shown clear evidence that the mass of supermassive black hole (SMBH) in the center of every galaxy is tightly correlated with the velocity dispersion of the bulge stars (Ferrarese & Merritt 2000; Gebhardt et al. 2000; Tremaine et al. 2002) and the mass of the whole bulge (Magorrian et al. 1998; McLure & Dunlop 2002; Marconi & Hunt 2003), which reflect the interplay with the nuclear activity and the spheroidal star formation activity (potential well depth of bulge stars). Recent consensus emphasizes that the nuclear black hole (BH) feedback is the sticking point to explain these correlations: the central BH can interact with the surrounding environment through BH feedback in a self-regulated way.

However, the tightness of the correlations indicated by both the observations and numerical simulations pose big challenge to many conventional feedback models, whose results are sensitive to the variable parameters such as gas fraction (the mass fraction of gas to dark matter) (Di Matteo et al. 2005). Recently, some modified feedback models have been proposed to alleviate the inconsistency. Begelman & Nath (2005) suggest that the BH accretion physics on local scale (relative to previous "global" models) should be considered. They consider that the "maximized" accreted gas mass will make the result insensitive to the gas fraction. Xu, Wu & Zhao (2007, hereafter XWZ07) provide another scenario to explain both the starburst activity in protospheroid and the BH-bulge relations. They suggest that the spheroid formation is "halo-regulated": the star formation is regulated by the background dark matter halo. In particular, the strong star-forming feedback acts outward to resist the gravity from the dark halo while acts inward to feed and obscure the central BH. Such scenario can naturally link the nuclear activity and outside star formation activity, and well explain the BH-bulge relations.

Here we revisit the idea of XWZ07 and find the "halo-regulated" mechanism can be generalized and simplified. We argue that it is possible that the stellar feedback can compress the surrounding gas and trigger the catastrophic star formation activity in a very dense environment when neglecting the heating effects. The intense starburst will make the star-forming region highly turbulent. The "maximized" turbulent sound speed, which is regarded as a measure of potential well depth of the protospheroid, can be reached when the whole system is in the virial equilibrium. Based on such "feedback compression" model, we show that once the assumption of homogeneous turbulent environment is valid, the star formation is regulated by the dark halo's gravity and regulates the central BH growth. The resultant BH-bulge relations are universal: only related to the velocity dispersion of stars and dark matter profile.

2. STAR FORMATION UNDER THE MOMENTUM FEEDBACK COMPRESSION

The merger induced starburst regions have very dense environment: the molecular gas density can be as high as $10^3 \sim 10^4 \mathrm{cm}^{-3}$ (Downes & Solomon 1998), much denser than that of disk galaxies. The cooling by collisionally excited atomic and molecular emission processes can be very efficient. Hence, we hypothesize that the heating feedback due to the ionization of HII region may be neglected comparing with the mechanical feedback in the starburst region. Since the shock-heated gas can quickly radiate their thermal energy, it is possible that the outward propagating shock can compress the surrounding gas into a gas shell in a momentum driven way and trigger the new star formation events. The result can be understood by a simple example: assuming that the expanding gas shell is thin, its dynamics can be described by

$$\frac{d}{dt}\left(R^3\frac{dR}{dt}\right) = \frac{3\dot{M}_w v_w}{4\pi\rho_0}, \tag{1}$$

where $\dot{M}_w$ is the mass loss rate, v_w is the velocity of wind and ρ_0 is the density of homogeneous gas around the stars. We can easily find the following solution at large R

$$R(t) = \left(\frac{3}{2}\frac{\dot{M}_w v_w}{\pi\rho_0}\right)^{1/4} t^{1/2}. \tag{2}$$

The shell will finally stall due to the ambient pressure, and we have the stalling radius $R_s = (\dot{M}_w v_w/4\pi n_0 kT)^{1/2}$. Using Eq. (2), the total compression timescale can be estimated as

$$t_c = \frac{\mu m_{H_2}}{4kT}\left(\frac{2\dot{M}_w v_w}{3\pi\rho_0}\right)^{1/2}. \tag{3}$$

Comparing t_c with the dynamical timescale $t_{dyn} = (3\pi/32G\rho)^{1/2}$, we have

$$\frac{t_c}{t_{dyn}} \approx 5\left(\frac{\rho_c}{\rho_0}\right)^{1/2} \dot{M}_6^{1/2} v_{500}^{1/2} T_{10}^{-1}, \tag{4}$$

where ρ_c is the gas density of the compressed gas shell, $\dot{M}_6 = \dot{M}_w/10^{-6}M_\odot yr^{-1}$, $v_{500} = v_w/500kms^{-1}$ and $T_{10} = T/10K$. Note that the shell gas density ρ_c is larger than ρ_0, so t_c is at least one order larger than t_{dyn}. It demonstrates that in a very dense environment, the density inhomogeneities are amplified by the feedback compression and the gas has enough time to collapse into the cloud.

The "light" outflow accelerating against the dense cold gas shell will trigger the Rayleigh-Taylor instability (RTI). Moreover, the Kelvin-Helmholtz instability (KHI) may also occur as the outflow punches into the gas shell and moves through the cold gas. The combination of these two instabilities will prevent the gas collapse and destruct the star-forming cloud. If the density contrast is large, the dispersion relation for RTI is $w \approx (ka)^{1/2}$ where a is the acceleration (Chandrasekhar 1961). The characteristic growth timescale for RTI responsible for the cloud destruction is $\tau_{RT} \approx (2\pi l_J/a)^{1/2}$ where l_J is the Jeans length. The acceleration can be derived from Eq. (2)

$$a(t) = \frac{1}{4}\left(\frac{3}{2}\frac{\dot{M}_w v_w}{\pi\rho_0}\right)^{1/4} t^{-3/2} \tag{5}$$

Initially, the growth timescale τ_{RT} may be smaller than the dynamical timescale t_{dyn}. The RTI will make the dense cold shell highly porous to the hot wind and entrain cold gas into the wind. The efficiency of driving wind enhances (Silk 2001). Note $\tau_{RT} \propto t^{3/4}$, we define the duration in which RTI dominates by setting $\tau_{RT} = t_{dyn}$. Using Eq. (5), the duration is

$$t_d = 2.5 \times 10^5 \dot{M}_6^{1/6} v_{500}^{1/6} n_3^{-1/2} T_{10}^{-1/3} \left(\frac{\rho_c}{\rho_0}\right)^{-1/3} yr, \tag{6}$$

where $n_3 = n_0/10^3 cm^{-3}$. The duration is smaller than the dynamical timescale t_{dyn}, which indicates that the cloud destruction by RTI and KHI (its growth timescale is of the same order as RTI's (Agertz 2006)) may not be important in the momentum driven phase, at least at large radius R. So it is reasonable to assume that the feedback induced compression can trigger and expedite the cloud collapse and the star formation.

3. "HALO-REGULATED" STAR FORMATION AND BLACK HOLE GROWTH

Star formation in the local disk galaxies is usually inefficient and the typical star formation efficiency (SFE) is $\sim 2\%$ (Kennicutt 1998). It is because that the star formation is regulated by the "negative" feedback (heating, blown out) to keep the star formation rate (SFR) from raising too high. However, as mentioned in the above section, it may not be the case in the starburst region. Without the heating effects, the feedback induced compression can serve as a "positive" feedback to trigger the intense star formation activities unless the total mechanical energy generated by the stellar feedback is larger than the binding energy of these regions. In another words, once the total feedback from those massive stars are unable to disrupt or unbind the whole star forming region, the star formation process may continue for a relatively long time, which is analogous to the formation of bound clusters (Elmegreen & Efremov 1997).

Following XWZ07, we adopt the NFW density profile for the background dark matter and assume the standard cosmological parameters with $\Omega_m = 0.3, \Omega_\Lambda = 0.7$ and $h = 0.7$ $(z = 0)$. The inner NFW profile is given by

$$\rho_{NFW}(r) \approx \Pi r^{-1}, \qquad \Pi \equiv 130 M_\odot \mathrm{pc}^{-2} M_{v,12}^{0.07} [\xi(z)]^{2/3} \Psi_{c,0.58}^{-1} \tag{7}$$

(Navarro, Frenk & White 1997; Komatsu & Seljak 2001), where $M_{v,12} = M_{vir}/10^{12} M_\odot$ and M_{vir} is the virial mass of the halo, $\xi(z) = [(\Omega_m/\Omega_m(z))(\Delta_c/100)]$, $\Omega_m(z) = [1+(\Omega_\Lambda/\Omega_m)(1+z)^{-3}]^{-1}$, $\Delta_c = 18\pi^2+82d-39d^2$ where $d = \Omega_m(z)-1$ (Bryan & Norman 1998; Barkana & Loeb 2001). $\Psi_{c,0.58} = [\ln(1+c) - c/(1+c)]^{-1}/0.58$ where $c \approx 13.4 M_{v,12}^{-0.13}(1+z)^{-1}$ is the concentration parameter (Bullock et al. 2001). Such r^{-1} profile in the inner region is almost a universal profile: it doesn't change by the galaxy merger or interaction, it is also insensitive to the redshift and the halo mass. Another interesting thing to note is that such inner profile gives a nearly constant gravitational acceleration

$$g_{\rm DM}(r) = \frac{GM_{DM}(r)}{r^2} = 2\pi G\Pi \sim 1.2 \times 10^{-8} {\rm cm\ sec}^{-2}. \tag{8}$$

Intense star formation activity and related stellar feedback will make the protospheroid environment highly turbulent. Because the bulge stars density distribution implies that the protospheroid density profile may follow $\rho \sim r^2$ (Tremaine et al. 1994), here we assume an isothermal density profile for the protospheroid baryon or mixture of gas and stars

$$\rho_b(r) = \frac{c_s^2}{2\pi G r^2}, \qquad M_b = \frac{2c_s^2 r}{G}, \tag{9}$$

where $\rho_b(r)$ is the total baryon density or density of the mixture of gas and stars, c_s is the "isothermal" turbulent sound speed and M_b is the enclosed mass within the radius r. The momentum transport during the compression requires that

$$\frac{\dot{P}_\star}{4\pi r^2} = \rho_b(r) c_s^2, \tag{10}$$

where $\dot{P}_\star$ is the net outward momentum deposition rate. The star formation activity and the feedback-induced turbulence will be maximized till the whole system evolves to a virial equilibrium state. Once the whole system becomes a little more turbulent, the deposited momentum flux will make the whole system deviate from the equilibrium state and the SFR is hence avoided from raising higher. Such a self-regulated mechanism will make the whole system maintain the equilibrium state.

We can write the equation of the virial equilibrium for the protospheroid as

$$3M_b c_{s,m}^2 = \frac{GM_b^2}{r} + \pi\Pi G M_b r, \tag{11}$$

where $c_{s,m}$ is the maximum turbulent sound speed. The first term of the right side of Eq. (11) denotes the total baryon's self-gravity while the second term denotes the gravity from the background dark matter. Substituting Eq. (9) into Eqs. (10) and (11), we obtain

$$\dot{P}_\star = \frac{2c_{s,m}^4}{G} = \pi\Pi G M_b. \tag{12}$$

Eq. (12) shows that the maximum turbulent sound speed or the potential well depth of the protospheroid is directly related to the background dark matter. In another words, both the star formation activity and the feedback compression are regulated by the dark halo's gravity as XWZ07 proposed. It only requires the homogeneous turbulent environment and the virial equilibrium, without involving the detailed gas assembly physics such as monolithic collapse or merger driven inflow. So the feedback compression combined with the halo regulation scenario provides a more general description to the star formation process during the spheroid formation.

Following XWZ07, during the formation of the protospheroid, the stellar feedback can act in both inward and outward directions. At small scale (e.g. galactic nuclear region), the inward stellar feedback (required to conserve the local momentum) obscures and regulates the BH growth, while the outward stellar feedback resists the gravity at large scale. In particular, the inward stellar feedback regulates the BH growth by interacting with the Compton-thick wind launched from the accretion disk if super-Eddington accretion is assumed (King & Pounds 2003). The final balance between the inward stellar feedback and the disk wind is achieved when

$$\dot{P}_\star = \frac{8\pi G M_{BH}}{\kappa} \tag{13}$$

where $\dot{P}_\star$ is the momentum flux transported by inward stellar feedback and the right side of Eq. (13) is the momentum deposition of the disk wind. Then if the BH's feedback is large enough to halt the further gas supply, and a BH will end its main growth phase after Eq. (13) is satisfied.

At a late epoch of the coeval evolution, star formation consumes most of gas and gradually fades away. Without continuous ejecting energy and momentum from the stellar feedback, the feedback-induced turbulence will decay on a crossing time of the system (Stone et al. 1998). Then the remaining stellar system will be virialized through violent relaxation under the combined gravity from itself and the background dark matter. We call the system at "initial state" after turbulence decay and before virialization, and at "final state" after virialization. Assuming the total energy of the initial state is E, the kinetic energy of the final virialized state is $K = -E$ according to the virial theorem. So we have

$$3\sigma_f^2 = 2\left(\frac{GM_b}{r} + \pi \Pi G r\right) = 6c_{s,m}^2. \tag{14}$$

Using Eq. (12), we obtain

$$\dot{P}_\star = \frac{\sigma_f^4}{2G}, \qquad r_b = \frac{\sigma_f^2}{2\pi\Pi G}, \tag{15}$$

where r_b is the boundary radius of the initial state. We note that the total momentum deposition rate from stars is only related to the velocity dispersion of the final stellar system, independent of any parameters of the detailed star formation physics.

Using Eqs. (13) and (15), we obtain the final BH mass

$$M_{BH}^{final} = \frac{\kappa\sigma_f^4}{16\pi G^2} = 1.5 \times 10^8 \sigma_{200}^4 M_\odot. \tag{16}$$

The result is remarkably consistent with the low-redshift observations (Tremaine et al. 2002). The stellar bulge mass is approximately equal to M_b. Using Eqs. (12) and (13), the ratio of BH mass to bulge mass can be expressed as

$$\frac{M_{BH}}{M_{bulge}} = \frac{\kappa\Pi}{8} \approx 1.4 \times 10^{-3} M_{v,12}^{0.07} [\xi(z)]^{2/3} \Psi_{c,0.58}^{-1}, \tag{17}$$

which matches the Magorrian relation found for the local galaxies (Magorrian et al. 1998; McLure & Dunlop 2002; Marconi & Hunt 2003).

4. APPLICATION TO THE HIGH-REDSHIFT STAR FORMING GALAXIES

The gas fraction of high-redshift galaxies is much larger than that of local galaxies. In an extremely case, we take the fraction ~ 1. In another words, the protospheroid with mass of M_b is almost totally in the gaseous form. Large amount of gas accumulating in the central region will trigger the central vigorous starburst accompanying with strong star-forming feedback. We mainly focus on two primary sources of star forming feedback: radiation pressure and supernovae. The combined momentum flux deposited in these star-forming feedback can be written as (Murray, Quataert & Thompson 2005; Xu, Wu & Zhao 2007)

$$\dot{P}_\star = \dot{P}_{rp} + \dot{P}_{sn} = \xi_m \epsilon \dot{M}_\star c, \tag{18}$$

where $\dot{M}_\star$ is the star formation rate and $\xi_m = 1 + \dot{P}_{sn}/\dot{P}_{rp}$ is of the order of unity in our model. Combining Eqs. (13), (16) and (18), we can easily obtain the star formation rate of high redshift starburst galaxies

$$\dot{M}_\star = \frac{\sigma^4}{2G\xi_m \epsilon c} \approx 600 \sigma_{200}^4 \xi_m^{-1} \epsilon_3^{-1} M_\odot yr^{-1}. \tag{19}$$

Although the star formation law in the protospheroid is far from clear, we adopt an equivalent Schmidt-Kennicutt Law in order to compare with the local disk galaxies (Schmidt 1959; Kennicutt 1998)

$$\dot{M}_\star = \eta \frac{M_b}{t_{dyn}}, \tag{20}$$

where η is the equivalent star formation efficiency and $t_{dyn} = (3\pi/32G\rho_g)^{1/2}$ is the dynamical time scale. In our model we take $\rho_g = 3M_b/4\pi r_b^3$ as the average gas density where r_b is the outer boundary radius given in Eq. (15).

From Eqs. (12) and (18), we have

$$\xi_m \epsilon \dot{M}_\star c = \pi \Pi G M_b. \tag{21}$$

Using Eq. (20) to eliminate $\dot{M}_\star/M_b$ in Eq. (21), we get the equivalent star formation efficiency as

$$\eta = \frac{\sqrt{2}\sigma_f \pi}{8\xi_m \epsilon c} = 0.4\sigma_{200}\xi_m^{-1}\epsilon_3^{-1}, \tag{22}$$

where $\epsilon_3 = \epsilon/10^{-3}$.

We find that our derived equivalent SFE is much higher than that in normal disk galaxies inferred from the Kennicutt Law, but is consistent with the high redshift star formation observations and some small scale star formation observation (eg. SFE in the formation of the protocluster). We note that the derived SFE is independent on the radius of the star-forming region and time, and the larger the velocity dispersion is, the higher the star formation efficiency is. Eq. (22) also gives us another implication for the maximum stellar velocity dispersion. We can rewrite Eq. (22) as

$$\sigma_f = \frac{4\sqrt{2}\xi_m \eta \epsilon c}{\pi}. \tag{23}$$

The physical limit requires $\eta \leq 1$, so the maximum stellar velocity dispersion is

$$\sigma_f^{max} = \frac{4\sqrt{2}\xi_m \epsilon c}{\pi} = 540\xi_m \epsilon_3 kms^{-1}. \tag{24}$$

According to Eq. (16), the maximum BH mass is $8 \times 10^9 M_\odot$.

Using Eqs. (12), (15) and the expression of t_{dyn} , we can also obtain the characteristic star formation timescale

$$\begin{aligned} t_\star &= \frac{t_{dyn}}{\eta} = \frac{2r_b \xi_m \epsilon c}{\sigma_f^2} = \frac{\xi_m \epsilon c}{\pi \Pi G} \\ &\approx 1.0 \times 10^8 \xi_m \epsilon_3 M_{v,12}^{-0.07} [\xi(z)]^{-2/3} \Psi_{c,0.58} yr. \end{aligned} \tag{25}$$

Through the feedback compression, the dark halo's gravity regulates the SFR and SFE to a higher level during the spheroid formation. We note that for some luminous elliptical galaxies whose velocity dispersion $\sigma \sim 300kms^{-1}$, the predicted star formation rate can reach as high as $3000 M_{\odot} yr^{-1}$, which is consistent with the observations of high-redshift starburst galaxies (Solomon & Vanden Bout 2005). It is also interesting to note that the star formation time scale is independent with velocity dispersion σ. Furthermore, the characteristic star formation time scale is larger than the salpeter time scale, which is usually taken to be the typical time scale for BH's growth. This means that the BH will first grow relatively fast to reach the balance condition (Eq. (13)) and then grow relatively slow to response the outside stellar feedback.

5. DISCUSSIONS

Unlike the previous momentum feedback models (King 2003; Murray, Quataert & Thompson 2005; Begelman & Nath 2005), which mainly focus on the BH feedback dynamics, our scenario considers more about the star formation activity in the protospheroid and its relation with the nuclear BH growth. Our model favors gas-rich environment at high-redshift because large amount of gas is needed to form stars and obscure the BH. We argue that at early epoch of BH growth (when BH is relatively small), large scale outflow or jet may not be crucial in producing BH-bulge relations although they become important after BH's main growth epoch (Churazov et al. 2002). In another words, BH doesn't generate outflow or jet till the balance condition Eq. (13) is satisfied. The derived $M_{BH} - \sigma$ relation based on our model is insensitive to the gas fraction and other variables, because the velocity dispersion is the measure of the maximized turbulent velocity of the total baryon component rather than the gas only, as Eq. (9) shows. The derived $M_{BH} - M_{bulge}$ relation has weak dependences on the redshift and the halo mass, which offer the intrinsic scatters to the relation.

Extremely high SFR and SFE are the results of certain "positive" feedback which is probably due to either "internal" or "external" effects. Silk (2005) suggest that the high SFR and SFE are triggered by the super-Eddington outflow driven by the SMBH. Such "external" positive feedback naturally leads to a top-heavy initial mass function (IMF) which is preferred by the early generation of star formation and predicts an antihierachical trend of SMBH growth (Merloni, Rudnick & Di Matteo 2004). However, recent optical, infrared and X-ray studies of SMGs indicate that SMGs harbour relatively smaller SMBH than that of typical quasars (Ivison et al. 1998; Vernet & Cimatti 2001; Smail et al. 2003; Alexander et al. 2005) and the main growth phase of SMBH ("pre-quasar" phase) is heavily obscured. Considering the SMGs themselves are massive galaxies which are reckoned as the progenitors of local ellipticals (Greve et al. 2005), the vigorous star formation activity can not be regulated by the small BH. Reversely, the star formation activity should have great impact on the small BH. So we argue that the "internal" positive feedback which is produced by the star formation itself may exist in some extremely dense starburst region at median redshift, and the SMBH outflow triggered star formation mode may only be available at very high redshift (Walter et al. 2004). In addition, the maximized "positive" stellar feedback is actually related to the dark halo's gravity in our model. Under the regulation of dark halo's gravity, the maximized velocity dispersion also has its maximum value, which is determined by the physical upper-limit of SFE. The physical upper-limit of BH mass ($\sim 10^{10} M_{\odot}$) can then be obtained by the $M_{BH} - \sigma$ relation, and the dynamical signature of such SMBHs should be detectable (Wyithe & Loeb 2003). We note that some observational evidence do support such result (Netzer 2003; Vestergaard 2004), although all of them still contain a lot of uncertainties. We expect more accurate SMBH mass measurements in the future to confirm our result.

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