EVOLUTION OF GASEOUS DISK VISCOSITY DRIVEN BY SUPERNOVA EXPLOSIONS
IN STAR-FORMING GALAXIES AT HIGH REDSHIFT

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ABSTRACT
Motivated by Genzel et al.’s observations of high-redshift star-forming galaxies, containing clumpy and turbulent rings or disks, we build a set of equations describing the dynamical evolution of gaseous disks with inclusion of star formation and its feedback. Transport of angular momentum is due to “turbulent” viscosity induced by supernova explosions in the star formation region. Analytical solutions of the equations are found for the initial cases of a gaseous ring and the integrated form for a gaseous disk, respectively. For a ring with enough low viscosity, it evolves in a slow process of gaseous diffusion and star formation near the initial radius. For a high viscosity, the ring rapidly diffuses in the early phase. The diffusion drives the ring into a region with a low viscosity and starts the second phase undergoing pile-up of gas at a radius following the decreased viscosity torque. The third is a sharply decreasing phase because of star formation consumption of gas and efficient transportation of gas inward forming a stellar disk. We apply the model to two $z \sim 2$ galaxies BX 482 and BzK 6004, and find that they are undergoing a decline in their star formation activity.

Key words: galaxies: evolution – galaxies: high-redshift

1. INTRODUCTION

Exciting progress has been made in observing assembly of gas and star formation in galaxies from low to high redshifts. Optically/UV-selected star-forming galaxies at $z \sim 0.5–2.5$ exhibit a fairly tight relationship between stellar mass and star formation rate, which is strongly suggestive of star formation happening with a high duty cycle (Noeske et al. 2007; Elbaz et al. 2007; Daddi et al. 2007). This may relate with random happening with a high duty cycle (Noeske et al. 2007; Elbaz et al. 2007; Daddi et al. 2007). This may relate with random

Distributions of density and angular momentum of a gaseous disk are generally controlled by the viscosity, if driven by viscosity of turbulence excited by SNexp, stellar distribution will be determined by this feedback process (Lin & Pringle 1987). The steady analytical solution of the circumnuclear disk of the Galaxy with the injection of SNexp energy has been obtained by Vollmer & Beckert (2003); coevolution of SMBHs and their hosts could be driven by SNexp-excited turbulence (Kawakatu & Wada 2008) as well as in the starburst–AGN connection in light of a strong correlation between the Eddington ratios and specific star formation rates (Chen et al. 2009). Figure 1 shows a clear trend of concentration of galaxies with star formation rate densities in the SINS sample given by Genzel et al. (2008), strengthening the interplay and regulation between SN explosions, cold gas accretion, and minor mergers.

In this Letter, we consider the secular evolution of gaseous disks, which could be formed during minor mergers, by including feedback from SNexp in star formation or burst regions characterized by the Hz ring in the SINS sample. We find the analytical solutions, which show two kinds of properties: (1) piled-up gas and (2) fast diffusion depending on the initial conditions of gas density. We apply the models to high-redshift galaxies.
of gas, and \( \dot{M}_\odot \) disk or escapes of winds from galaxies. Star formation process

et al. 2005),

4 All the parameters

\[ \frac{\partial}{\partial t} (\Sigma R^2 \Omega) + \frac{\partial}{\partial R} (R V_R \Sigma R^2 \Omega) - \frac{1}{2 \pi} \frac{\partial G}{\partial R} + R^3 \Omega \Sigma = 0. \] (2)

where \( G = 2 \pi R^3 \nu \sigma (d \Omega / d R) \) is the viscosity torque, \( \nu \) is kinematic viscosity, and \( \Omega \) is the angular velocity. Combining Equations (1) and (2), we have

\[ \frac{\partial \Sigma}{\partial t} = - \frac{1}{2 \pi R \partial R} \left\{ d \left( R^2 \Omega \right) \right\}^{-1} \frac{\partial G}{\partial R} - \dot{\Sigma}. \] (3)

In this Letter, we explore the role of viscosity driven by SNexp in the secular evolution of gaseous disks. Similar to Kawakatu & Wada (2008), we assume that the vertical structure is supported by turbulence pressure

\[ \frac{P_{\text{turb}}}{H} = \rho_{\odot} \left( \frac{G M_\bullet H}{R^3} + \pi G \Sigma \right) \approx \rho_{\odot} \frac{\sigma^2}{R}, \] (4)

where \( M_\bullet \) is the black hole mass, \( G \) is the gravity constant, \( \Omega = \sqrt{2 \sigma / R} \) and \( \pi G \Sigma = \sigma^2 / R \) are used (Equation (1) in Thompson et al. 2005), \( P_{\text{turb}} = \rho_{\odot} V_{\text{turb}}^2 \) is the turbulence pressure, \( \sigma \) is the dispersion velocity of galaxies determined by the total potential of gas, stars, and dark matter halo, and \( H \) is the half-thickness of the disk. The validity of solutions presented here is limited by the potential used in Equation (4), namely, \( GM_\bullet H / R^3 \lesssim \sigma^2 / R \), we

thus have, \( R \gtrsim GM_\bullet (H / R) / \sigma^2 \approx 10 M_\odot \sigma^2 / (H / R) \) pc, where \( M_\bullet = M_\odot / 10^8 \) and \( \sigma_{200} = \sigma / 200 \) km s\(^{-1}\). The energy equation of turbulence excited by SNexp is given by Wada & Norman (2002)

\[ \frac{\rho_{\odot} V_{\text{turb}}^2}{t_{\text{dis}}} = \frac{\rho_{\odot} V_{\text{turb}}^2}{H} = \xi \dot{S}_*, E_{\text{SN}}, \] (5)

where \( t_{\text{dis}} = H / V_{\text{turb}} \) is the timescale of the turbulence, \( \xi \) is the efficiency converting kinetic energy of SNexp into turbulence, \( S_* \) is the SNexp rate, and \( E_{\text{SN}} \) is the SNexp energy. SNexp rate strongly depends on the initial mass functions, but we absorb its uncertainties into the parameter \( \xi \) and simply let \( S_* \) be the star formation rate.

The viscosity law \( \nu = \alpha V_{\text{turb}} H \) is assumed commonly, where \( \alpha \) is the viscosity parameter (Shakura & Sunyaev 1973). The Kennicutt–Schmidt’s law displays \( \Sigma_* \propto \Sigma^{1.4} \), however, there is growing evidence for a linear relation for denser environment in star-forming galaxies from numerical simulations (Dobbs & Pringle 2009; Krumholz et al. 2009). We use \( \Sigma_* = c_\Sigma \Sigma \) for star-forming galaxies at high redshift, where \( c_\Sigma \) is a constant. We thus have the energy equation \( V_{\text{turb}}^3 \) of turbulence excited by SNexp is given by Wada & Pringle (2008). We should keep in mind that there are two different aspects from the classical gaseous disk investigated by Lynden-Bell (1974): (1) radius-dependent viscosity driven by SNexp and (2) dropout of mass and angular momentum due to star formation on the disk. These drive some interesting properties of gaseous disks.

3. SOLUTIONS: EVOLUTIONARY PROPERTIES

3.1. Gaseous Ring

A realistic initial condition is a single gaseous ring, which can be formed via one minor merger (Hernquist & Mihos 1995). Equations (3)–(6) have analytical solutions for the case of a single ring. After some algebraic operations (e.g., Kato et al. 1998), we have the analytical solution for the case

\[ \Sigma(r, \tau) = \frac{\Sigma_0}{2 \pi} \frac{1}{r^3} \left( \frac{q_0}{\tau} \right)^{1 / 2} \left( 1 - e^{-\frac{r}{\tau}} \right) e^{-\tau - \frac{\Omega}{\omega} (\tau - 1)}, \] (8)
where \( \Sigma_0 = M_0/\pi R_0^2 \), \( \tau = c_s t \), \( r = R/R_0 \), and \( M_0 \) is the total mass of the initial ring at a radius \( R_0 \), and the dimensionless parameter \( q_0 \) is defined by

\[
q_0 = \frac{c_s}{4\pi R_0^2} = 0.5844 c_{s,0}^{-1} c_{s,8}^{-2} R_{0,1}^{-2} (\xi_{-3} E_{51})^{-3} \sigma_{200}^8,
\]

where \( R_{0,1} = R_0/10 \) kpc.

Complicated evolutionary behaviors of the surface density are determined by \( q_0 \) values as shown in Figure 2. For a given \( q_0 \leq q_c = 0.544 \), there are two sets of roots of \( \partial \Sigma / \partial r = 0 \) and \( \partial \Sigma / \partial \tau = 0 \), corresponding to the peak and valley of the envelope of the \( \Sigma \)-evolution track at \( r_p \) and \( \tau_p \). Otherwise there is no root of the two equations, namely, there is no peak or valley of the envelope. Evolution of \( \Sigma(r, \tau) \) and \( \Sigma_t(r, \tau) \) can be found in Figures 3(a) and (b), respectively. We show three types of solutions: (1) \( q_0 < q_c \), (2) \( q_0 = q_c \), and (3) \( q_0 > q_c \). The \( q_0 > q_c \) solutions are quite simple and similar to the pure diffusion of a gaseous ring described in Lynden-Bell & Pringle (1974). The ring dramatically spreads over the space and forms stars. A stellar ring forms then as shown in Figure 3(b) \( q_0 = 2 \) panel. For \( q_0 = q_c \) solution, there is a flat envelope without peak and valley, forming a very broader stellar ring as shown in Figure 3(b) \( q_0 = 0.544 \) panel.

The \( q_0 < q_c \) solutions have complicated behaviors as shown in Figure 3(a) \( q_0 = 0.1 \) panel. Evolution of the gas ring can be divided into three phases. At early time, star formation is only important in the role of transportation of angular momentum, and the mass dropout can be neglected. Behaviors of the ring are very similar to the pure fluid ring. The gas rapidly diffuses inward mostly and outward a little bit carrying away the angular momentum. Though the star formation rates are very high, the total formed stars are not many since the duration of this phase is quite short. The second phase begins when mass dropout due to star formation becomes important. Decrease of the gas density is leading to decrease of star formation and weakening the viscosity torque of SNexp, resulting in accumulation of gas at the radius \( r_p \). The third phase starts when the viscosity torque is enhanced in light of the gas accumulation. This causes intensive star formation and exhausts gas, giving rise to an exponential decreases of gas density.

To understand such behaviors of solutions, we compare the timescales of star formation (\( t_* = 1/c_{s,0} \)) and gas advection (\( t_{adv} = R/V_r \approx R^2/v = 1/\xi R^2 \)). According to the \( q_0 \)-definition, it follows \( t_{adv}/t_* = 4q_0 \). When \( t_* \ll t_{adv} \) at \( R_0 \) (roughly corresponding to \( q_0 \ll q_c \)), most of the gas is converted into stars at \( R_0 \) and only a little gas is conveyed inward. In contrast, in the \( t_* > t_{adv} \) case (namely, \( q_0 \ll q_* \)) at initial radius \( R_0 \), star formation is so slow that most of the gas is advected inward. For a case with initial \( q_0 \ll q_* \), most of gas is advected inward until \( t_{adv} > t_* \). Pile-up of gas appears at \( r_p \) then and forms stars. The complicated behaviors of gas density are the result of a consequence of competition between the two processes.

Figure 3(b) shows the surface density of stars for the corresponding gas density. For \( q_0 = 0.1 \), the gas rapidly diffuses inward and there is no significant pile-up of stars at the initial radius \( R_0 \). A stellar ring forms at roughly \( ~0.15R_0 \) far away from its initial radius. The ring becomes broader with increases of \( q_0 \). When \( q_0 = q_* \), there begins to be a tiny pile-up of stars at the initial radius. For a case with a large \( q_0 \), pile-up of stars happens very close to the initial radius and it becomes more conspicuous with \( q_0 \). The stellar rings become wider with \( q_0 \). Figure 3(c) displays evolution of the Toomre parameter \( Q \), clearly showing \( Q < 1 \) in the star-forming region. \( Q \)-values are quite different in different regions. This strengthens the importance of self-gravity in the secular evolution of the gaseous disk. Since \( Q \propto \Sigma_{gas}^{-1} \), \( Q \) basically follows the evolution of \( \Sigma_{gas} \). A generic property of the \( Q \)-parameter is that it increases with time since the gas is being converted into stars. This is totally different from the steady gaseous disk with star formation under the presumed condition of \( Q = 1 \) suggested by Thompson et al. (2005).

We would like to point out that the feedback from SNexp will be enhanced, if we use the nonlinear Kennicutt–Schmidt’s law to calculate the star formation rate, leading to more efficient
The instability of the gaseous disks can be simply justified by the operating mechanism of the viscosity. When gas is piled up, the higher star formation rates can efficiently remove the angular momentum of gas, and then suppress the star formation rates. The system should be self-organized and stable. However, we should give a detailed description of stability analysis in a future paper.

4. APPLICATIONS

Dynamics of the gaseous disk presented here allow us to compare the current model with Genzel et al.’s observations of star-forming galaxies at high redshift. Observations of SINFONI on ESO VLT provide details of the “cold gas” accretion. We choose two galaxies as illustrations to apply the present theoretical model. BX 482 is a ring-dominated star-forming galaxy, of which the ring radius is $R_{\text{ring}} = 7.0 \pm 0.8$ kpc with a narrower width $\Delta R \sim 1$ kpc, its dispersion velocity is $\sigma = 210$ km s$^{-1}$ and the surface density of star formation rates is $0.57 \pm 0.3 M_\odot$ yr$^{-1}$ kpc$^{-2}$. We hence choose the ring model (Equation (8)). The bright H$\alpha$ ring limits the lifetime of the ring, which is about $\sim 10^7$ yr in light of OB stars. The left column of Figure 5 gives the dynamical evolution of the ring. The Toomre parameter $Q$ shows that the ring is self-gravity dominated. A stellar ring formed in the gaseous ring is still growing shown by the red line, but the H$\alpha$ ring is becoming dimmer.

BzK 6004 is also a rotation-dominated galaxy with a relatively faint but broader H$\alpha$ ring ($\Delta R/R \sim 1.0$ from Figure 5 in Genzel et al. 2008). The ring radius is $R_{\text{ring}} = 6.9 \pm 0.8$ kpc and the dispersion velocity of galaxy is $\sigma = 240$ km s$^{-1}$ and the surface density of star formation rate is $0.6 \pm 0.3 M_\odot$ yr$^{-1}$ kpc$^{-2}$. The current data do not allow us to distinguish the case of different $\gamma$ we thus just use $\gamma = 2$ as an illustration. The dynamical evolution of the galaxy is shown by the red line in the right
column of Figure 5. The current stage of the ring is approaching the end state of star forming. The stellar ring is still growing fast and may remain as a wide stellar ring. The $Q$-value shows that self-gravity is also dominated.

We note that the solutions presented here tend to show an exponential stellar disk if the time is long enough. This agrees with the steady disks known for quite a long time from Lin & Pringle (1987). The simple application of the current model shows here that SNexp does indeed play a key role in the dynamical evolution of the gaseous rings or disks. However, the application should be improved with the more detailed data. For example, the good-quality data of the Hα ring profile and the spatially resolved spectroscopy will allow us to get the evolution stage of gas and star formation from the stellar synthesis. Particularly, the very sharp inner edge of the ring predicted here is caused by SNexp. This reflects feedback of the star formation. Additionally, application of the present model to a large sample (e.g., Föster Schreiber et al. 2009) will produce the initial conditions of the sample for a statistics in future. This will be invaluable to justify the origin of the cold gas.

We would like to stress here that the present applications focus on the main features of galaxies at high redshift. The ring or disk models for the two galaxies are less conclusive. We need more information on the galaxies, such as stellar ages at different ring radii, so as to give more robust pictures. Degeneracies of parameters limit applications of the model.

5. CONCLUSIONS

We set up a model of a gaseous disk with star formation, in which the viscosity is driven by turbulence excited by SNexp. We get the analytical solutions for the initial condition of a single gas ring, showing complicated secular evolutionary behaviors. Several different kinds of stellar distributions can be formed, including exponential types. The present model is able to reproduce starburst rings in two galaxies as illustrations.

The model will be improved in several aspects in the future by using: (1) nonlinear star formation law, (2) separated equations of stars and gas, and (3) initially twisted gaseous disk (Lu & Cheng 1991). These will help us to determine the initial conditions as a consequence of minor mergers and allow us to study the evolution of stellar disks and bulges.

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REFERENCES

Bournaud, F., Jog, C. J., & Combes, F. 2007, A&A, 476, 1179
Bower, R. G., et al. 2006, MNRAS, 370, 645
Brooks, A. M., et al. 2009, ApJ, 694, 396
Chen, Y.-M., Wang, J.-M., Yan, C.-S., Hu, C., & Zhang, S. 2009, ApJ, 695, L130
Daddi, E., et al. 2007, ApJ, 670, 156
Davé, R. 2008, MNRAS, 385, 147
Dekel, A., et al. 2009, Nature, 457, 451
Dib, S., Bell, E., & Burkert, A. 2006, ApJ, 638, 797
Dib, S., et al. 2009, arXiv:0903.2241
Dobbs, C. L., & Pringle, J. E. 2009, MNRAS, 396, 1579
Elbaz, D., et al. 2007, A&A, 468, 33
Föster Schreiber, N. M., et al. 2006, ApJ, 645, 1062
Föster Schreiber, N. M., et al. 2009, ApJ, in press (arXiv:0903.1872)
Genzel, R., et al. 2006, Nature, 442, 786
Genzel, R., et al. 2008, ApJ, 687, 59
Guo, Q., & White, S. D. M. 2008, MNRAS, 384, 2
Hernquist, L., & Mihos, C. 1995, ApJ, 448, 41
Kato, S., Fukue, J., & Mineshige, S. 1998, Black-Hole Accretion Disks (Kyoto University Press), 571
Kawakatu, A., & Wada, K. 2008, ApJ, 681, 73
Kitzbichler, M. G., & White, S. D. M. 2007, MNRAS, 376, 2
Krumholz, M. R., McKee, C. F., & Tumlinson, J. 2009, ApJ, 693, 216
Law, D. R., et al. 2007, ApJ, 669, 929L
Lin, D. N. C., & Pringle, J. E. 1987, ApJ, 320, L87
Lu, J.-F., & Cheng, F.-H. 1991, Science China A (in Chinese), 9, 971
Lynden-Bell, D., & Pringle, J. E. 1974, MNRAS, 168, 603
Mac Low, M.-M., & Klessen, R. S. 2004, Rev. Mod. Phys., 76, 125
Naab, T., et al. 2007, ApJ, 658, 710
Noeske, K. G., et al. 2007, ApJ, 660, L43
Shakura, N. I., & Syunyaev, R. 1973, A&A, 24, 337
Tacconi, L., et al. 2006, ApJ, 640, 228
Tacconi, L., et al. 2008, ApJ, 680, 246
Thompson, T., Quataert, E., & Murray, N. 2005, ApJ, 630, 167
Vollmer, B., & Beckert, T. 2003, A&A, 404, 21
Wada, K., & Norman, C. 2002, ApJ, 566, L21
Wang, J.-M., Chen, Y.-M., Yan, C. S., & Hu, C. 2008, ApJ, 673, L9
Wang, J.-M., Chen, Y.-M., & Zhang, F. 2006, ApJ, 647, L17
Wang, J.-M., et al. 2009, ApJ, 697, L14
Wright, S. A. 2007, ApJ, 658, 78