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Co-Evolution Model of AGNs and Nuclear Starbursts

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Abstract. We propose a new evolutionary model of a supermassive black hole (SMBH) and a circumnuclear disk (CND), taking into account the mass-supply from a host galaxy and the physical states of CND. In the model, two distinct accretion modes depending on gravitational stability of the CND play a key role on accreting gas to a SMBH. (i) If the CND is gravitationally unstable, energy feedback from supernovae (SNe) supports a geometrically thick, turbulent gas disk. The accretion in this mode is dominated by turbulent viscosity, and it is significantly larger than that in the mode (ii), i.e., the CND is supported by gas pressure. Once the gas supply from the host is stopped, the high accretion phase changes to the low one (mode (ii)), but there is a delay with $\sim 10^8$ yr. Through this evolution, the gas-rich CND turns into the gas poor stellar disk. We found that not all the gas supplied from the host galaxy to the central 100 pc region accrete onto the SMBH even in the high accretion phase (mode (i)), because the part of gas is used to form stars. Moreover, a super-Eddington accretion is possible in the high accretion phase and thus the its condition is briefly discussed.

1. Introduction

The energy emitted by active galactic nuclei (AGNs) is commonly ascribed to accretion onto a supermassive black hole (SMBH). The physics of angular momentum transfer in a galaxy is inevitable for formation of SMBHs because of 9 orders of magnitude difference in their size scale. So far, there are number of mechanisms to accumulate the gas on kpc scale down to the galactic central region, e.g., the tidal torque driven by the major and minor merger of galaxies (e.g., Mihos & Hernquist 1994, 1996) and the stellar bars (e.g., Shlosman et al. 1990), a gas drag and dynamical friction in the dense stellar cluster (Norman & Scoville 1988) and the radiation drag (Umemura 2001; Kawakatu & Umemura 2002). However, the accumulated gas does not accrete onto a SMBH directly, since the angular momentum of the gaseous matter cannot be thoroughly removed. Thus, some residual angular momentum would terminate the radial infall, so the accreted gas forms a reservoir, i.e., a circumnuclear disk (CND), in the central ∼100 pc around a SMBH whose scale depends on the angular momentum. If the gas is dense enough, we expect star formation in this region. The active star formation has been actually observed in nearby Seyfert galaxies (e.g., Imanishi & Wada 2004; Davies et al. 2007; Watabe et al. 2008). The nuclear starburst must affect the SMBH growth because the radiation and/or supernova feedback due to starbursts can trigger the mass accretion onto a SMBH (e.g., Umemura et al. 1997; Wada & Norman 2002). In order to reveal the final mass accretion rate to the BH region, it is crucial to link mass accretion processes from a galactic scale with those from an accretion disk in the vicinity of a central BH, via the CND. To this aim, we here propose a new model of a nuclear starburst disk supported by the turbulent pressure led by supernova explosions (for the radiation pressure supported CND, see Thompson et al. 2005). In our model, the turbulent excited by supernova transports the angular momentum. Our model presented here relies on the results of three-dimensional hydrodynamic simulations done by Wada & Norman (2002). We show how SMBH grows from a seed BH, taking into account the mutual connection between the mass-supply from a host galaxy and the physical states of the CND accompanied by the star formation following Kawakatu & Wada (2008).

2. Models

We presuppose that the dusty gas is supplied around a central SMBH at a rate of $\dot{M}_{\rm sup}$ from a host galaxy whose surface density, $\Sigma_{\rm host}$, including the gas and stellar components, is constant in time. The accumulated gas forms a turbulent pressure-supported clumpy CND around a central SMBH with $M_{\rm BH}$. We here assume the isothermal cold gas ($T_{\rm g} = 50 - 100\,{\rm K}$) in the CND since the dust cooling is effective (Wada & Tomisaka 2005).

2.1. Turbulent Pressure-Supported CND

We describe the physical settings of the CND supported by the turbulent pressure via the SN explosions. On the vertical structure of CND, we assume that the turbulent pressure associated with SN explosions is balanced to gravity, g caused by

$$\rho_{\rm g}(r)v_{\rm t}^2(r) = \rho_{\rm g}(r)gh(r), \tag{1}$$

where $\rho_{\rm g}(r)$, $v_{\rm t}(r)$ and $h(r)$ are the gas density, the turbulent velocity and the scale height of the disk, respectively. Here, the gravity, g is obtained as $g \equiv GM_{\rm BH}h/r^3 + \pi G(\Sigma_{\rm disk}(r) + \Sigma_{\rm host})$ where $\Sigma_{\rm disk}(r)$ is the surface density of baryonic components (the gaseous matter and stars)

The geometrical thickness is determined by the balance between the turbulent energy dissipation and the energy input from SN explosions as follows.

$$\frac{\rho_{\rm g}(r)v_{\rm t}^2(r)}{t_{\rm dis}(r)} = \frac{\rho_{\rm g}(r)v_{\rm t}^3(r)}{h(r)} = \eta S_*(r)E_{\rm SN}, \tag{2}$$

where the dissipation timescale of the turbulence, $t_{\rm dis}(r) = h(r)/v_{\rm t}(r)$, $E_{\rm SN}$ is the total energy (10^{51} erg) injected by an SN, η is heating efficiency per unit mass which denotes how much energy from SNe is converted to kinetic energy of the matter, and the star formation rate per unit volume and time is $S_*(r) = C_*\rho_{\rm g}(r)$. Here C_* is the star formation efficiency which is constant in time.

2.2. Two Regimes of Gas Accretion in CND

We suppose a kinetic viscosity as a source of angular momentum transfer in the gas disk. Then, the mass accretion rate in a viscous accretion disk is given by

$$\dot{M}(r) = 2\pi\nu\Sigma_{\rm g}(r)\left|\frac{d\ln\Omega(r)}{d\ln r}\right|, \tag{3}$$

where the viscous parameter is $\nu_{\rm t}(r) = \alpha v_{\rm t}(r)h(r)$ and the angular velocity $\Omega(r)$ is given by the radial centrifugal balance. We define the growth rate of SMBH, $\dot{M}_{\rm BH}$ as $\dot{M}_{\rm BH} \equiv \dot{M}(r_{\rm in})$, where the inner radius of the disk is determined by the dust sublimation radius, i.e., $r_{\rm in} = 3\,{\rm pc}\,(M_{\rm BH}/10^8 M_\odot)^{1/2}$. At $r_{\rm in}$, we assume the CND connectes with the steady accretion disk. With respect to the stability, we adopt Toomre's stability criterion, i,e., when the surface density of gas in the disk, $\Sigma_{\rm g}$ is higher (lower) than the critical surface density, $\Sigma_{\rm crit}$ the disk is gravitationally unstable (stable). The critical surface density is obtained as $\Sigma_{\rm crit}(r) = \kappa(r)c_{\rm s}/\pi G$, where $\kappa(r) \equiv 4\Omega(r)^2 + 2\Omega(r)rd\Omega(r)/dr$ is the epicyclic frequency and $c_{\rm s}$ is the sound velocity. The critical radius $r_{\rm c}$ is determined by the Toomre criterion, that is, $\Sigma_{\rm g}(r_{\rm c}) = \Sigma_{\rm crit}(r_{\rm c})$. In this picture, it is natural that there are two modes of gas accretion rate as follows: *mode (i):* If $r_{\rm c} < r_{\rm in}$ (fully gravitationally unstable), then the disk is geometrically thick due to stellar energy feedback, and as a result we have a large accretion rate. We here suppose $\alpha = 1$ motivated by numerical simulations demonstrated by WN02. *mode (ii):* If $r_{\rm c} > r_{\rm in}$, the scale height of the inner region would be much smaller than mode (i), because the scale height is determined by the thermal pressure, $P_{\rm g}(r) = \rho_{\rm g}(r)gh_{\rm th}(r)$ where $P_{\rm g}(r) = \rho_{\rm g}(r)c_{\rm s}^2$. In the mode (ii), the magneto-rotational instability could be a source of turbulence, but the turbulent velocity is comparable or even smaller than the sound speed (e.g., Balbus & Hawley 1991; Machida et al. 2000). As a result, the accretion is less efficient than the mode (i). We assume $\alpha = 0.5$ and $v_{\rm t} = c_{\rm s}$. Since the critical radius and the inner edge of the disk are functions of the BH mass, and surface density of the gas, and the gas mass depends on the star formation rate in the gas disk, the evolution of the whole system (a central BH plus a CND) should be time-dependent.

2.3. SMBH Growth and States of the Circumnuclear Disk

Our main purpose is to evaluate the time-evolution of SMBH growth and the star formation rate and gas mass in the disk by focusing on the time dependence of characteristic radius in the disk ($r_{\rm c}$, $r_{\rm in}$, and $r_{\rm out}$), instead of solving the evolution of radial structure of disk. Then, the surface density of disk is assumed by a power law with the cylindrical radius r as $\Sigma_{\rm disk}(r) = \Sigma_{\rm disk,0}(r/r_{\rm out})^{-\gamma}$, where $r_{\rm out}$ is the outer boundary of the disk. In this model the supplied gas from the host galaxy is eventually consumed to form the SMBH or stars. Then, the BH mass and gas mass in the disk are simply given by the mass conservation as follows: The time-evolution of the gas mass in the disk, $M_{\rm g} \equiv \int_{r_{\rm in}}^{r_{\rm out}} 2\pi r'\Sigma_{\rm g}(r')dr'$, is given by

$$M_{\rm g}(t) = \int_0^t [\dot{M}_{\rm sup}(t') - \dot{M}_*(t') - \dot{M}_{\rm BH}(t')]dt', \tag{4}$$

where $\dot{M}_{\rm sup}(t)$, $\dot{M}_*(t)$ and $\dot{M}_{\rm BH}(t)$ are the mass-supply rate from hosts, the star formation rate, and the growth rate of SMBH, respectively. On the other hand, the time-evolution of SMBH mass $M_{\rm BH}(t)$ is obtained as $M_{\rm BH}(t) = M_{\rm BH,seed} + \int_0^t \dot{M}_{\rm BH}(t')dt'$, where we assume the mass of seed BHs, $M_{\rm BH,seed} = 10^2 M_\odot$, as end-products of the first generation stars (e.g., Heger et al 2003). For $\dot{M}_{\rm sup}$, we can assume any function for the mass supply rate, but here we simply take a step function as the first attempt as $\dot{M}_{\rm sup}(t) = const$ for $t < t_{\rm sup}$, while $\dot{M}_{\rm sup}(t) = 0$ for $t > t_{\rm sup}$ where $t_{\rm sup}$ is a period of the mass-supply from hosts.

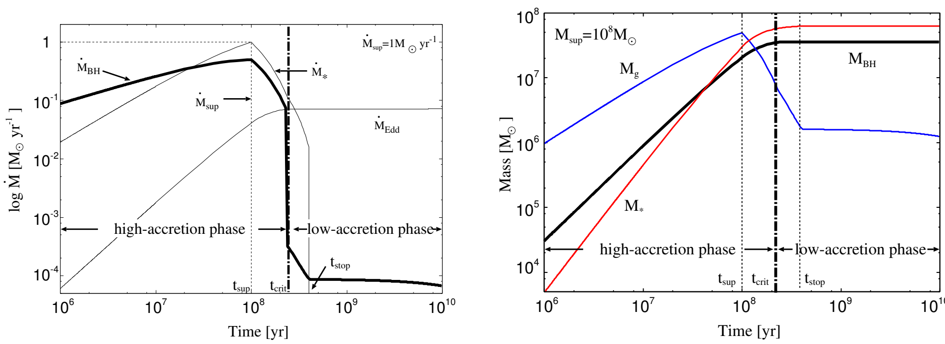

Figure 1. *Left*: Time evolution of $\dot{M}_{\rm BH}(t)$, $\dot{M}_*(t)$, $\dot{M}_{\rm sup}(t)$ and $\dot{M}_{\rm Edd}(t)$ for $\dot{M}_{\rm sup} = 1\,M_\odot\,{\rm yr}^{-1}$ and $t_{\rm sup} = 10^8\,{\rm yr}$. $t_{\rm sup}$ is a period of the mass-supply from hosts. $t_{\rm crit}$ is the time when $r_{\rm c} = r_{\rm in}$. $t_{\rm stop}$ is the time when the massive disk is gravitationally stable, that is, $\Sigma_{\rm g} < \Sigma_{\rm crit}$ for the entire massive disk. We call the phase ($t < t_{\rm crit}$) the high-accretion phase, while we call the phase ($t > t_{\rm crit}$) the low-accretion phase. The star formation efficiency C_* is $3\times10^{-8}\,{\rm yr}^{-1}$ which is the value of nearby starburst galaxies (Wada & Norman 2007). *Right*: Time evolution of the mass of BH (black solid line), $M_{\rm BH}(t)$, the gas mass in the disk (blue solid line), $M_{\rm g}(t)$, and the stellar mass in the disk (red solid line), $M_*(t)$. The total supplied mass from host galaxies, $M_{\rm sup}$ is $10^8\,M_\odot$.

3. Results

3.1. The Growth Rate of SMBHs and Star Formation Rate

We examine how the growth rate of SMBHs is related to the star formation rate in the CND. Figure 1 (left) shows the time evolution of $\dot{M}_{\rm BH}(t)$, $\dot{M}_*(t)$, and $\dot{M}_{\rm Edd}(t) \equiv L_{\rm Edd}(t)/c^2$ for $\dot{M}_{\rm sup} = 1\,M_\odot\,{\rm yr}^{-1}$ and $t_{\rm sup} = 10^8\,{\rm yr}$, where $L_{\rm Edd}$ is the Eddington luminosity. As seen in Fig. 1 (left), we find that not all the gas supplied from a host galaxy reaches to the SMBH, i.e., $\dot{M}_{\rm BH} = 0.1 - 0.3 M_\odot\,{\rm yr}^{-1}$ for $\dot{M}_{\rm sup} = 1\,M_\odot\,{\rm yr}^{-1}$ even in the high accretion phase. This high accretion phase drastically changes to the low accretion phase with $\dot{M}_{\rm BH} \sim 10^{-4} M_\odot\,{\rm yr}^{-1}$. But, there is a delay with $\sim 10^8\,{\rm yr}$ after the mass supply is stopped. This time-lag is basically determined by the star formation efficiency, C_*. In the high accretion pahse, we find that $\dot{M}_{\rm BH} \approx (0.1 - 5)\dot{M}_*$. In the turbulent supported CND, such a high accretion rate is led by the high conversion efficiency from the energy input from SN explosions to the accretion energy ($\approx 1 - 10\%$). In the early epoch of the SMBH growth, a super-Eddington mass accretion rate ($\dot{M}_{\rm BH} \gg \dot{M}_{\rm Edd}$) is maintained for $\sim 10^8\,{\rm yr}$.

3.2. Evolution of Gas, SMBH and Stellar Masses

We here elucidate the physical difference between two phases for SMBH growth (high- and low- accretion phases). We plot the mass of SMBH, $M_{\rm BH}(t)$, gas mass in the disk, $M_{\rm g}(t)$, and stellar mass in the disk, $M_*(t) \equiv \int_0^t \dot{M}_*(t')dt'$ in Fig. 1 (right). The total supplied gas mass from the hosts, $M_{\rm sup} \equiv \dot{M}_{\rm sup} t_{\rm sup}$, is $10^8\,M_\odot$. In the high accretion phase, plenty of gas accumulate around a SMBH since $\dot{M}_{\rm sup}(t) > \dot{M}_{\rm BH}(t)$ as seen in Fig. 1 (left). Thus, the mass ratio of gas in CND and SMBH, $m_{\rm disk} \equiv M_{\rm g}/M_{\rm BH}$ is about ten and the gas fraction to the total baryonic mass, $f_{\rm g} \equiv M_{\rm g}/(M_{\rm g}+M_*)$, is close to ≈ 1. Recalling that the accretion is a super-Eddington in high accretion phase, large $m_{\rm disk} > 1$ and $f_{\rm g} \sim 1$ could be the conditions which the super-Eddington mass accretion can keep. Moreover, we find that the saturation of SMBH growth appears $\sim 10^8\,$yr later after the mass supply is stopped.

4. Summary

We have constructed a new model of SMBH growth, taking into account the evolution of physical states of the circumnuclear disk formed by the mass-supply from the host galaxy. In the present model, we consider the two regimes of gas accretion depending on the gravitational stability of the disk. We found that not all the gas in the disk accrete onto the SMBH, i.e., $\dot{M}_{\rm BH} = 0.1-0.3M_\odot\,{\rm yr}^{-1}$ for $\dot{M}_{\rm sup} = 1\,M_\odot\,{\rm yr}^{-1}$ because the part of gas is used to form stars in the disk. This high accretion phase changes to the low accretion phase with $\dot{M}_{\rm BH} \sim 10^{-4}M_\odot\,$yr. But the transition takes $\sim 10^8\,$yr after the mass supply from hosts is stopped. In the high accretion phase, a super-Eddington accretion is possible, and thus the existence of gas rich circumnuclear disks ($M_{\rm g} > M_{\rm BH}$) is a condition which the super-Eddington accretion onto a central SMBH keeps. In the present model, the two phases of SMBH growth depend on whether stars can form in the inner region of the circumnuclear disk. This could imply that the BH growth rate depends on the spatial distribution of young stars in the CND. In order to explore this, infrared observations with high spatial resolution are crucial, because young stars would be buried in the optically thick CND.

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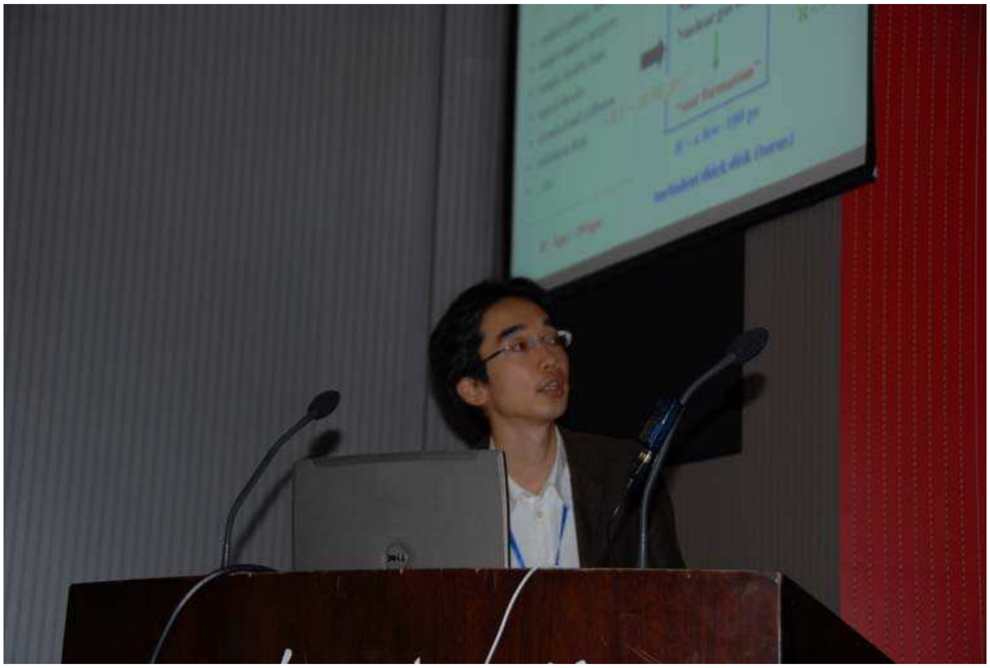

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Questions from Todd Thompson