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SECULAR EVOLUTION OF BARRED GALAXIES

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ABSTRACT

Owing to several observational evidences and theoretical predictions for morphological evolution of galaxies, it is now widely accepted that galaxies do evolve from late types to early ones along the Hubble sequence. It is also well established that non-axisymmetric potentials of bar-like or oval mass distributions can change the morphology of galaxies significantly during the Hubble time. Here, we review the observational and theoretical grounds of the secular evolution driven by bar-like potentials, and present the results of SPH simulations for the response of the gaseous disks to the imposed potentials to explore the secular evolution in the central regions of barred galaxies.

Key words : galaxies: barred - galaxies: spirals - method: numerical simulations

I. INTRODUCTION

Secular evolution of galaxies is a dynamical evolution which transforms the structure of galaxies in a Hubble time. It takes place essentially in all the galaxies but its effect is most pronounced in the barred galaxies where the non-axisymmetric potential from the bar component drives the secular evolution faster than others. Spiral arms do play the same role as bar (Zhang 1996, 1998, 1999), but the driving force is weaker than that of the bar. The pioneering idea on the secular evolution in barred galaxies was suggested by Kormendy (1979, 1982) from the morphology of the bright barred galaxies. He proposed a hypothesis that there exists a process which makes some bars evolve fairly rapidly to a nearly axisymmetric state, lens. At the time of Kormendy's hypothesis, there was no theoretical or numerical studies that supports the secular evolution hypothesis.

A decade later, Pfenniger & Norman (1990) proposed a more bold hypothesis based on the gas responses in the 3D barred potentials that secular evolution along the Hubble sequence (from late types to early ones) is a natural consequence of the resonant heating induced by central mass concentration driven by the bars. Friedli & Martinet (1993), based on self-consistent 3D simulations (gas+ star), suggested that the secular evolution of galaxies may lead to the sequence of evolution as SBc − > SBb − > SBa or S − > SB − >S. The former sequence is due to the bulge growth process (Pfenniger & Norman 1990), while the latter is driven by the bar destruction mechanism (Hasan & Norman 1991). If we combine these two process, the secular evolution may follow the sequence like Sc − > SBc − > SBb − > Sb or Sc − > SBb − > Sba − > Sb0 − > S0.

More detailed studies on the secular evolution of barred galaxies were performed by Friedli & Benz (1993, 1995) using 3D PMSPH code. Friedli & Benz (1993) showed that triaxial bulges can be formed by the destruction of bars due to high central mass concentration caused by the large amount of mass inflow driven by the bars. By incorporating the star formation process in PMPSH code, Friedli & Benz (1995) clearly showed that newly formed stars in the central regions are likely to get out of the plane by vertical resonances, forming the bulges.

The sense of secular evolution in galaxies is the direction of increasing entropy, i.e., evolving toward more relaxed shape because it is basically a dissipative process. Because of the dissipative nature, it is an irreversible process, and the evolution from late types to early ones is very natural. Moreover, it seems to be self-regulated since the increase of central mass concentration from the mass inflow driven by the bar leads to the destruction of the bar itself (Hasan, Pfenniger, & Norman 1993; Norman, Sellwood and Hasan 1996).

Since the secular evolution of galaxies which transforms the galaxy morphology takes place in the long time scale (~ Hubble time), it is difficult to see the transformation of global morphology even in the numerical models. However, the evolution in the central regions of barred galaxies is fast enough to see the morphological changes in current numerical simulations. Thus, here we explore the morphological evolutions of the nuclear regions of barred galaxies by conducting hydrodynamical simulations for the gas response to the imposed potentials.

This paper is organized as follows. In next section, we describe the observational evidences for the secular evolution in galaxies. The formation and evolution of bars are briefly reviewed in §3, and the results of the SPH simulations for the evolution of gaseous disks in the central regions of barred galaxies are given in §4. The final section summarizes our conclusions.

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II. OBSERVATIONAL EVIDENCES

There are several observational evidences which support the secular evolution hypothesis of galaxy morphology. The fast rotation of triaxial bulges in barred galaxies (Kormendy 1982) is one of the earlier observations that support the secular evolution hypothesis because the fast rotation of triaxial bulges can be explained if the triaxial bulges are made of stars formed from the disk material which are transported to the central regions by the secular evolutionary process. The preponderance of the triaxial bulges in barred galaxies (Show et al.. 1995; Wozniak et al.. 1995; Ann 1995) supports the secular evolutionary scenario of the formation of the triaxial bulges since the non-axisymmetric potentials are known to be effective to drive disk material into the nuclear regions of barred galaxies (Simkin, Su, & Schwarz 1980; Schwarz 1984; Combes and Gerin 1985; Friedli & Benz 1993). The radial mass inflow is greatly enhanced when there is a central mass concentration such as supermassive black hole that creates horizontal and vertical resonances through which weakly dissipative particles can rapidly traverse (Pfenniger & Norman 1990). The triaxial bulges can also be the results of disk heating due to the vertical resonances caused by the central mass concentration and broadened by the non-axisymmetric perturbations (Pfenniger & Norman 1990).

The boxy/peanut-shaped bulges mainly observed in edge-on galaxies (Jarvis 1986; Shaw 1987, 1993; Shaw & Dettmar 1990; Lutticke, Dettmar, & Pohlen 2000) are also supposed to be made by secular evolutionary process such as bar-buckling mechanism proposed by Combes et al.(1990) and Raha et al.(1991). The bar-buckling mechanism as the origin of the boxy/peanut-shaped bulges are supported by the recent spectroscopic observations of boxy/peanut-shaped bulges (Bureau & Freeman 1999) which showed that almost all boxy/peanut-shaped bulges are due to a thick bar viewed edge-on. However, Lutticke et al.(2000) argued that there are boxy/peanut-shaped bulges which show no signature of the presence of bars from the NIR observations of 60 edge-on galaxies. Rather, they suggested that boxy/peanut-shaped bulges are different from bars because their sizes are smaller than the bars. Another promising mechanism to produce the boxy/peanut-shaped bulges is the disk heating from the vertical resonances between rotating bar and disk stars (Pfenniger 1984; Pfenniger & Friedli 1991). As shown by Pfenniger & Norman 1990), the disk heating is enhanced when there is a central mass concentration.

Some bulges, especially late type bulges are known to have exponential luminosity profile similar to that of disk (Andredakis & Sanders 1994; Courteau et al.1996; Carollo 1999). This correlation between the scale lengths of bulges and disks is suggested to be established by the secular evolution of galaxies (Courteau, de Jong, & Broeils 1996), where bulges are formed from the disk material which are transported into the central region by the torques from the non-axisymmetric disturbances (Combes et al.1990; Pfenniger & Friedli 1991). Recent hydrodynamical simulations in CDM cosmology (Saiz et al.2001) show the secular evolution processes that leads to the formation of the double exponential nature of disk and bulge. The coupling between the bulge and disk scale lengths found from the decomposition of the luminosity profile of late type spirals in the *BVRH* bandpasses (MacArthur, Courteau, and Holtzman 2003) supports the aforementioned secular evolution scenarios again.

Secular evolution affects the luminosity distribution of disk too. The Freeman's (1970) type II disk of which luminosity profile is characterized by the shallow gradient with central cut-off (Freeman 1970; Kormendy 1977) is found to be preponderant in barred galaxies where bars drive secular evolution (Ann 1997). Similar, but relatively weak tendency for barred galaxies to have a higher occurrence of type II disks was found by Baggett, baggett, & Anderson (1998). The redistribution of disk materials by non-axisymmetric disturbances such as bars, which lead to the formation of type II disk, is reproduced by n-body simulations (Norman et al.1996).

The effect of secular evolution on the morphology of galaxies are most prominent in the central regions of galaxies. The nuclear spirals, nuclear bars, and nuclear rings reported in the recent high resolution observations of spiral galaxies (Maoz et al.1996; Carollo, Stiavelli, & Mack 1998; Regan & Mulchaey 1999; Perez-Ramirez 2000; Pogge & Martini 2002) seem to manifest the undergoing secular evolution driven by the non-axisymmetric components. A good example of the nuclear features that is explained by the secular evolution process driven by the bars is the nuclear ring/spiral of NGC 4314 (Benedict et al.1992, 1996). The hydrodynamical models of Ann (2001) clearly showed that they are formed from the disk material driven by the bar.

The absence of barred galaxies at high redshifts (Abraham et al.1999; Merrifield 2002), which is contrary to the predominance of barred galaxies at the present epoch, demonstrates the secular evolution that transforms the global morphology of galaxies in Hubble time. There seems to almost no barred galaxies beyond a redshift of $z \approx 0.5$. The reason for the deficit of barred galaxies beyond $z \approx 0.5$ is not clear because there is no observational data that can distinguish the proposed mechanisms, including dynamically hotter disks at high redshifts and enhanced efficiency in bar destruction at high redshifts. However, whatever the mechanism is responsible for, there should be secular evolution in barred galaxies during the Hubble time.

III. FORMATION AND DESTRUCTION OF BARS

It has been well known that cold self-gravitating disks are unstable to the formation of bar (Hockney &

Hohl 1969; Miller, Prendergast,& Quirk 1970; Kalnajs 1972; James & Sellwood 1978; Hohl & Zhang 1979). This theoretical prediction is consistent with the preponderance of barred galaxies in nearby universe. However, we need mechanisms to suppress the bar forming instability in the self-gravitating cold disks because one third of the nearby galaxies have no bar at all. One promising mechanism to stabilize the cold disks was proposed by Ostriker & Peebles (1973) by introducing massive dark halo surrounding the disk of spiral galaxies. Until recently, the massive dark halo hypothesis seems to work, as noted by recent N-body simulations (Debattista & Sellwood 2000; Athanassoula & Misiriotis 2002), but halos can stimulate the bar instability by taking the positive angular momentum from the disk/bar component, especially at the resonance locations (Athanassoula 2003). Moreover, bars can also be grown by the disk particles trapped into the bar (Sellwood 1981). Thus, there is virtually no way to suppress the formation of bars unless disks are too hot to be unstable.

This leads to the question why do all disk galaxies not have bars since the self-gravitating cold disks are likely to be the outcomes of dissipational collapse of proto-clouds in isolated galaxy formation (Larson 1976; Fall & Eftathiou 1980) or galaxy formation in hierarchical CDM cosmology (White & Rees 1978; Silk 2003, reference therein). Thus, there seems to be an effective mechanism that leads to the destruction of bars within a fraction of Hubble time. There are several mechanisms that destroy bars but the most plausible mechanism for the destruction of bars in disk galaxies is the development of central mass concentration. Hasan & Norman (1990) showed that the elongated orbits that support the bar are likely to be dissolved if the central mass concentration is sufficient enough to produce the ILR radius comparable with the bar minor axis. Norman et al.(1996) showed that the central mass concentration exceeding $\sim 5\%$ of the bulge and disk mass can destroy bars completely. Thus, the evolution of disk galaxies seems to be self-regulating since the building up of the central mass concentration by the radial gas inflow and disk heating is a runaway process driven by bar (Pfenniger & Norman 1990). The formation of a bar in a cold disk drives secular evolution that build up the central mass concentration which eventually destroy the driving engine, bar.

The absence of barred galaxies at high redshifts (Abraham et al.1999) indicates that bars have developed more recently. The late epoch of bar formation is consistent with the prediction of the recent numerical simulations for the disk galaxy formation in the framework of Λ CDM cosmology (Abadi et al.2003). This also agrees with the earlier prediction of Combes & Sanders (1981) who showed that strong bars have not persisted since the epoch of galaxy formation which are thought to be earlier than $z \sim 1$.

IV. EVOLUTION OF CENTRAL REGIONS OF BARRED GALAXIES

Because the dynamical time scales in the central regions of galaxies is shorter than those of the outer part of galaxies, the effect of secular evolution on the morphology of galaxies is most pronounced in the nuclear regions of galaxies. The nuclear features recently observed in the high resolution observations, such as nuclear spirals, nuclear bars, and nuclear rings are supposed to be transient features made by the secular evolution processes driven by non-axisymmetric components. Here, we present the results of some numerical simulations for the response of gaseous disks to the imposed potentials, including the bars and supermassive black holes (SMBHs). The numerical method we have employed is smoothed particle hydrodynamics (SPH) incorporated with particle mesh algorithm for the computation of the self-gravity of gas particles. See Ann & Lee (2000) and Ann & Thakur (2003) for more detailed descriptions of the mass models and the numerical methods.

(a) Nuclear Rings

Nuclear rings of spiral galaxies is supposed to be transient features because most of them are composed of young stellar populations. A good example is the nuclear ring of NGC 4314 (Benedict et al.1992, 1996). Ann (2001) reproduced the nuclear ring morphology by SPH simulations based on the mass models derived from the surface photometry of the galaxy. As shown by Ann & Lee (2000), formation of nuclear ring requires the existence of ILRs when there is no SMBH and the sound speed in the gas is assumed to be 10km/s. However, nuclear rings can be formed in galaxies with SMBH which is massive enough to remove the IILR (Ann & Lee 2003).

Fig. 1 shows some examples of the evolution of nuclear rings in models with nearly the same mass models except for the masses of SMBH and initial gaseous disk. The number in the upper left corner of each diagram represents the evolution time in the unit of 10^6 yr. The hydrodynamical properties such as sound speed in the gas and the artificial viscosities are kept the same for all the models. The model M1 is characterized by the mass of the gaseous disk as $M_{gas}/M_G = 0.01$, while the models M2 and M3 assume the mass of the gaseous disk as $M_{gas}/M_G = 0.05$. The self-gravity of gas in the model M1 is negligibly small compared with other forces, but it affects the evolution of the gaseous disk significantly in the models M2 and M3. The only difference between the model M2 and M3 is the mass of SMBH. We assumed a SMBH with $M_{SMBH} = 0.01 M_G$ in M3, whereas we assumed no SMBH in M1 and M2. As shown clearly, a very sharply defined dense nuclear ring is developed, which is aligned perpendicular to the bar axis, in the model M1, while loosely defined nuclear rings whose shapes reflect the spiral patterns that are developed in the early phase of evolution are formed in the models M2 and M3. But all the nuclear rings are located nearly at the same radius that corresponds to the position of the peak of the $\Omega - \kappa/2$ curve in the models with no SMBH. Because the only difference between the model M1 and M2 is the mass of the initial gaseous disk, the self-gravity of gas, which is significantly larger in M2 model, makes the morphological difference. Besides this difference, as can be seen in Fig. 1, a thin secondary ring is formed at IILR within which no particle can reside in M1, while the secondary ring formed near IILR is eventually collapsed due to their own self-gravity in the model M2. But, in the case of the nuclear ring of M3 model, the strong gravity of SMBH helps the gas particles to move inward in a curling spiral manner.

The morphology of the nuclear ring developed in M3 model is somewhat similar to the nuclear ring of NGC 4314 (Benedict et al.1996) in the sense that they look like ring-like spiral. However, the orientation of the nuclear ring of NGC 4314 is almost aligned with the primary bar (Benedict et al.1996; Ann 2001), while that of the nuclear ring in M3 is almost perpendicular to the bar. Moreover, NGC 4314 is known to have a nuclear bar (Benedict et al.1996; Ann 2001). Thus, the physical conditions which lead to the formation of the nuclear ring of NGC 4314 are somewhat different from those assumed in M3. The assumed sound speed of gas in the model M3 seems to be too low for the interstellar medium of the nuclear regions of galaxies that host SMBHs since there is a correlation between the sound speed of gas and the potential shape in the nuclear regions (Englmaier & Shlosman 2000; Ann & Thakur 2003). Since there seems to be nuclear bar as well as nuclear ring/spiral (Benedict etal 1996; Ann 2001), it is highly plausible that NGC 4314 does not have SMBH or hosts a SMBH much less massive than that assumed in the model M3.

(b) Nuclear Spirals

Nuclear spirals are known to be preponderant in normal spiral galaxies as well as in active galaxies (Phillips et al. 1996; Regan & Mulchaey 1999; Martini & Pogge 1999; Pogge & Martini 2002). The morphology of nuclear spirals, as shown in Martini et al.(2003), displays from the symmetric two-armed spiral to chaotic one. Because of the diversity of morphology, there seems to be no clear understanding of how they form. However, it is quite certain that most of the nuclear spirals are transient ones and are formed by the disk material that is transported to the nuclear region due to loss of angular momentum by dynamical frictions from the non-axisymmetric components such as bars.

Here we present some results of SPH simulations which show the development of nuclear spirals. Since the evolution of the gaseous disk depends much on the self-gravity of gas when the mass of the gaseous disk is larger than $\sim 5\%$ of the galaxy mass (Ann & Lee 2000), we take into account the effect of the self-gravity of gas along with the viscosities in the simulations. Fig. 2 shows several snap shots of the time evolution of the nuclear regions of the gaseous disks under the same potentials but with different initial mass of the gaseous disks (M4 and M5) and with different sound speeds in the gas (M5 and M6). All the models have identical mass models including the mass of SMBH which amounts to 1% of the galaxy mass. The models M4 and M5 assume sound speed of gas as $C_s = 15$ km/s, while the model M6 assumes $C_s = 5$ km/s. As shown in Fig. 2, there seems to be no big difference between the general shapes of the nuclear spirals in M4 and M5 except for the somewhat bigger size and less symmetry in the model M5. But, the evolution of M6 shows much different nuclear morphology which displays development of chaotic nuclear spirals in the early times of the evolution, which settles down to a more symmetric one in later times. If we consider that the only difference between M5 and M6 is the sound speed of gas, it is apparent that the self-gravity of gas plays a critical role in the evolution of the cold gaseous disks. Similar, but more chaotic, evolution is found in the models with small or no SMBH. Thus, the chaotic nuclear spirals might be formed in the interstellar medium which is cold enough for the gravitational instability to play dominant roles in the nuclear regions of galaxies.

V. CONCLUSIONS

As we described above, secular evolution of galaxies is no longer a hypothesis but a dynamical process by which the morphology of a galaxy changes continuously. The morphology of a galaxy that we see today may be much different from the initial one. There are a plenty of observational evidences that support the secular evolution scenarios. Some of them are the fast rotation of triaxial bulges, occurrence of boxy/peanut shaped bulges, type II disks, and the correlation between the scale lengths of disks and bulges of spiral galaxies. The direction of evolution, from late types to earlier ones, is in agreement with that expected from the virial theorem for the self-gravitating system, i.e., towards higher rotational velocities and higher central binding energy (Pfenniger & Norman 1990).

The engine of the secular evolution is known to be the non-axisymmetric potentials which cause dynamical frictions to exchange the angular momentum of the disk materials. The bar-buckling and disk heating mechanisms are some of the promising mechanisms proposed to explain the boxy/peanut shaped bulges and triaxial bulges. Halo also plays a critical role in the formation and evolution of a bar that drives the secular evolution in barred galaxies. Contrary to the long-standing belief, halo can stimulate the bar instability by depriving the angular momentum of the bar. However, the formation and evolution of a bar is a self-regulated process that ends with the destruction of the bar by the central mass concentration which was caused by the bar driven mass inflow.

Nuclear morphology provides much information about

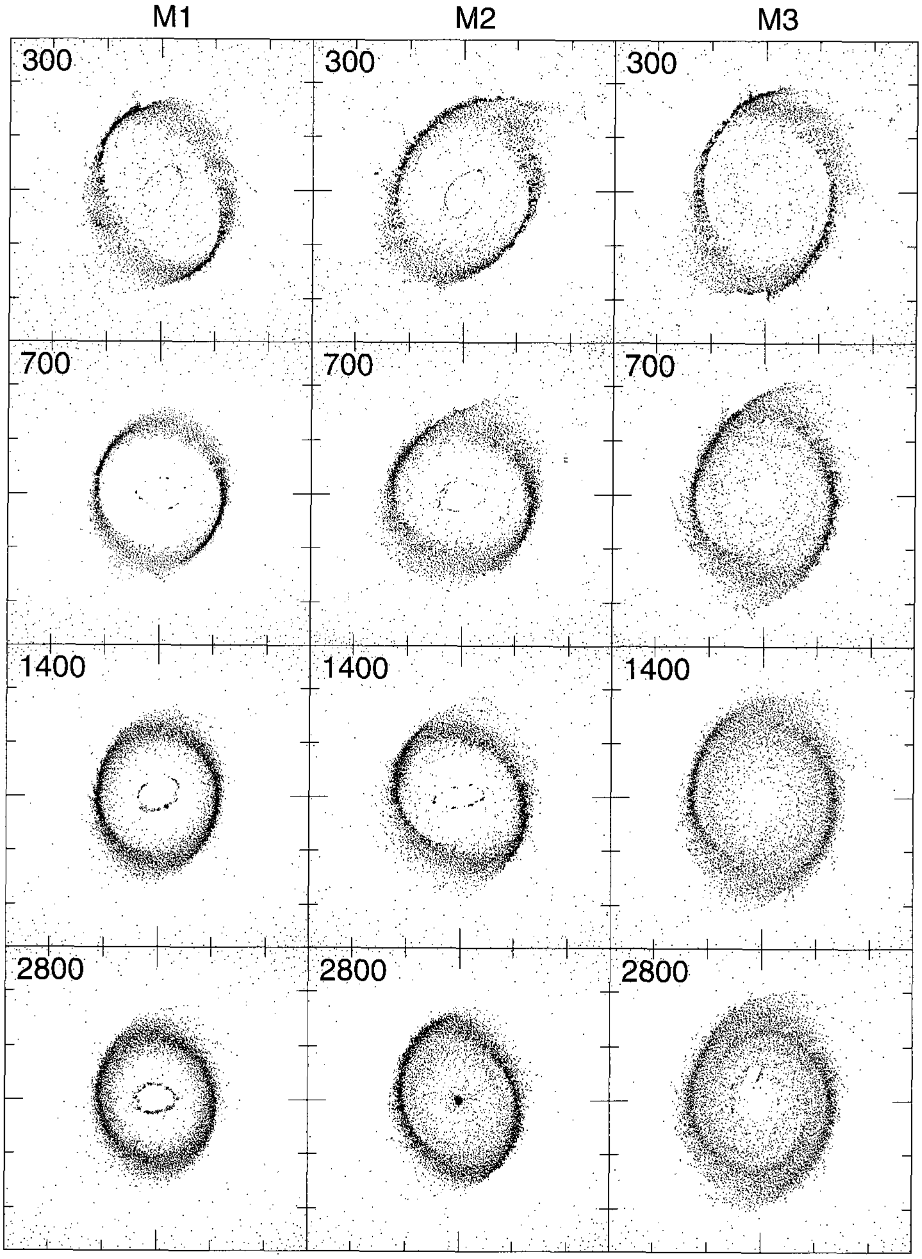

Fig. 1.— Snap shots of time evolution of gaseous disks that show nuclear ring morphologies. All the models have the same mass models except for the masses of SMBH and the gaseous disk. We assumed $M_{SMBH} = 0.01 M_G$ in M3, while $M_{SMBH} = 0$ in M1 and M2. The mass of the initial gaseous disk is 1% of the galaxy mass in M1 and 5% in M2 and M3. The sound speed of gas is 5 km/s in all the models. The numbers in the upper left corners of diagrams are the evolution times in unit of 10^6 yr. The length of each side of a panel is 2.8 kpc.

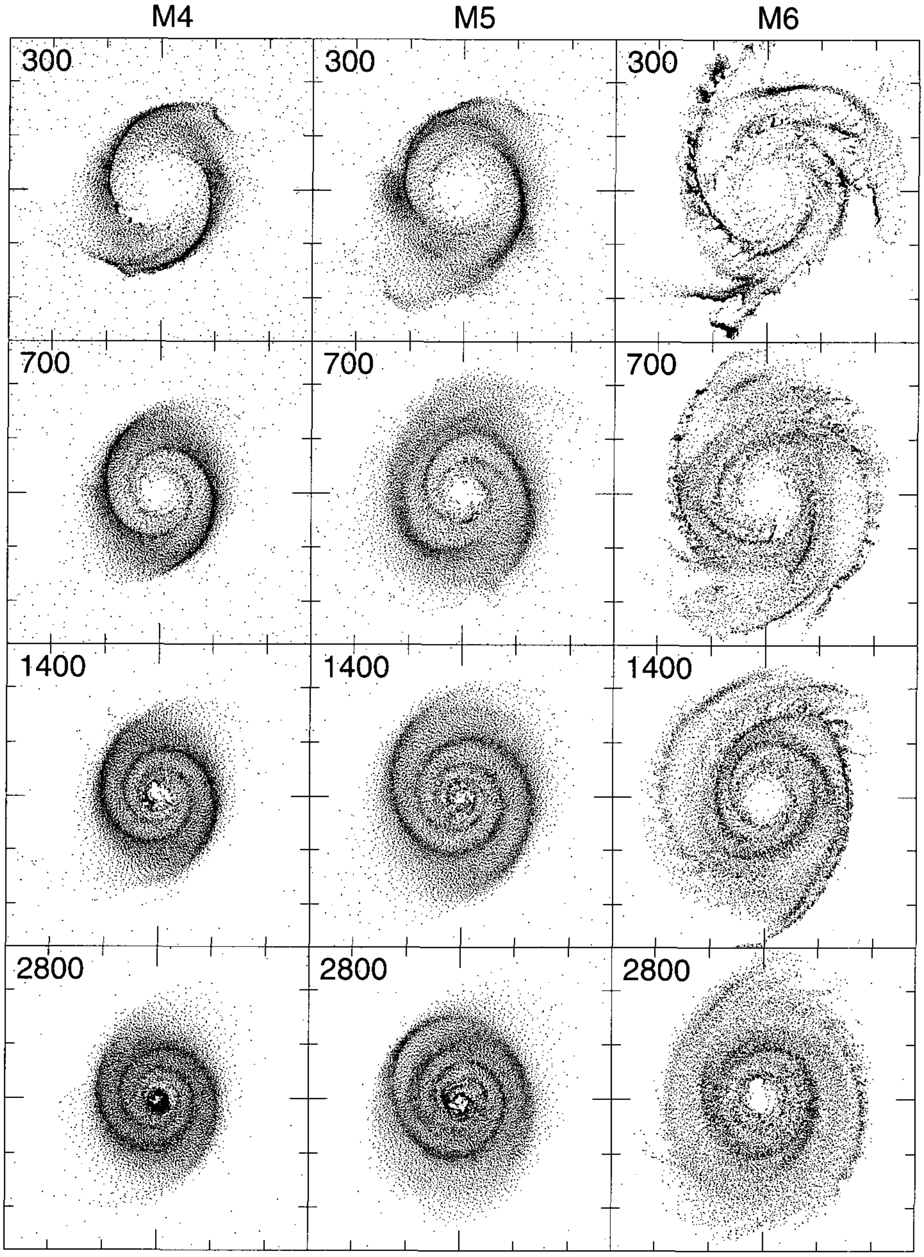

Fig. 2.— Snap shots of time evolution of gaseous disks that show nuclear spiral morphologies. All the models have the same mass models except for the mass of the gaseous disks: $M_{gas} = 0.01M_G$ in M4 and $M_{gas} = 0.05M_G$ in M5 and M6. The mass of SMBH is assumed to be $M_{SMBH} = 0.01M_G$ for all the models. The sound speeds of gas are assumed to be 15 km/s in M4 and M5 whereas that of M6 is 5 km/s. The length of each side of a panel is 2.8 kpc.

the on-going secular evolution. The nuclear rings and nuclear spirals are well reproduced by the hydrodynamical models with self-gravity of gas. As was noted by Ann & Lee (2000), formation of a nuclear ring requires the presence of ILRs when there is no SMBH. However, it is also possible that nuclear rings form without IILR when there is a SMBH that is massive enough to remove the IILR in the cold interstellar medium (C_s = 5km/s). Nuclear spirals are known to be the dominant features that have a diversity of morphologies. The grand design, symmetric nuclear spirals appear to be formed in hotter interstellar medium (i.e., large sound velocity), while the chaotic ones are likely to be formed in the cold interstellar medium which is dense enough for the self-gravity of gas to play dominant role over the hydrodynamical forces.

We understand somewhat the nature of secular evolution in galaxies. But, there are still several important issues to be solved. We really do not understand the formation and evolution of bars which are believed to be the engine of the secular evolution. When and how does the bar form?

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