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Ultraviolet-background-induced bifurcation of galactic morphology

Hajime Susa★ and Masayuki Umemura★

Centre for Computational Physics, University of Tsukuba, Tsukuba 305, Japan

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ABSTRACT

Based upon a novel paradigm of galaxy formation under the influence of an ultraviolet background, the evolutionary bifurcation of pre-galactic clouds is compared with observations of elliptical and spiral galaxies. The theory predicts that the dichotomy between dissipational and dissipationless galaxy formation stems from the degree of self-shielding from the ultraviolet background radiation. This is demonstrated on a bifurcation diagram of collapse epochs versus masses of pre-galactic clouds. Using the observed properties, the collapse epochs and mass are assessed for each type of galaxy. By direct comparison of the theory with observations, it turns out that the theoretical bifurcation branch successfully discriminates between elliptical and spiral galaxies. This suggests that the ultraviolet background radiation could play a profound role in the differentiation of galactic morphology into the Hubble sequence.

Key words: molecular processes – radiative transfer – galaxies: formation.

1 INTRODUCTION

A substantial basis of galaxy formation theory has been developed by several pioneering studies in the 1970s (Rees & Ostriker 1977; Silk 1977). The theory predicts that galactic scales are basically determined by atomic cooling of hydrogen and helium. The pre-galactic evolution is elegantly summarized in the 'cooling diagram' for virialized objects. Moreover, the origin of Hubble types has been attributed to the dissipativeness of the collapse, which is regulated by the efficiency of star formation. If the star formation proceeds after most of the gravitational energy has dissipated, the pre-galactic clouds will evolve into spiral galaxies. This is a paradigm of so-called dissipational galaxy formation (e.g. Larson 1976; Carlberg 1985; Katz & Gunn 1991). On the other hand, an early star formation episode leads to dissipationless galaxy formation (e.g. Aarseth & Binney 1978; Aguilar & Merritt 1990), ending up with the formation of elliptical galaxies. However, the key mechanism that physically controls the star formation efficiency has been hitherto undiscovered.

Very recently, Susa & Umemura (2000, hereafter SU) have proposed that self-shielding against ultraviolet background radiation regulates the star formation in pre-galactic clouds. The star formation processes in primordial gas have been explored by many authors with *ab initio* calculations (e.g. Matsuda, Sato & Takeda 1969; Hutchins 1976; Carlberg 1981; Palla, Salpeter & Stahler 1983; Susa, Uehara & Nishi 1996; Uehara et al. 1996; Omukai & Nishi 1998; Nishi et al. 1998; Nakamura & Umemura 1999). The key physics is the radiative cooling by H_2 line emission, because H_2 is the only coolant for primordial gas at $T \lesssim 10^4$ K. SU have studied the efficiency of H_2 cooling in collapsing clouds exposed to ultraviolet background radiation, because it is significant after the reionization of the Universe, probably at $z \lesssim 10$ (Nakamoto, Umemura & Susa 2000, and references therein). SU have found that, if a cloud undergoes the first sheet collapse at higher redshifts ($z \gtrsim 4$), then the cloud is quickly shielded against the ultraviolet background and consequently cools down owing to the efficient formation of H_2. As a result, it leads to an early burst of star formation. On the other hand, the shielding is retarded for a later-collapsing cloud at $z \lesssim 4$, resulting in dissipational galaxy formation. As a result, the bifurcation branch of the self-shielding corresponds to the boundary between dissipationless and dissipational galaxy formation. In this paper, this novel bifurcation theory is compared with observations of elliptical and spiral galaxies to determine whether or not the theory is successful in practice.

2 BIFURCATION THEORY

In Fig. 1, we show the bifurcation theory. Here, the cosmological parameters are assumed to be $\Omega = 0.3$, $h = 0.7$ and $\Omega_b h^2 = 0.02$ with the usual meanings. Originally, the sheet collapse was pursued with two initial parameters, i.e. the mean density ($\bar{n}_{\rm ini}$) and the thickness (λ). Here, the initial parameter space is translated into the baryonic mass [$M_b \equiv (4\pi/3)\bar{n}_{\rm ini}(\lambda/2)^3$] and the collapse epoch (z_c) by assuming that the initial stage is close to the maximum expansion of a density fluctuation. In region (a) in Fig. 1, a pre-galactic cloud is self-shielded against the external ultraviolet radiation in the course of the sheet collapse, so that the cloud cools down below 10^3 K and undergoes efficient star formation. Hence it is expected to evolve into an early-type galaxy

★ E-mail: susa@rccp.tsukuba.ac.jp (HS); umemura@rccp.tsukuba.ac.jp (MU)

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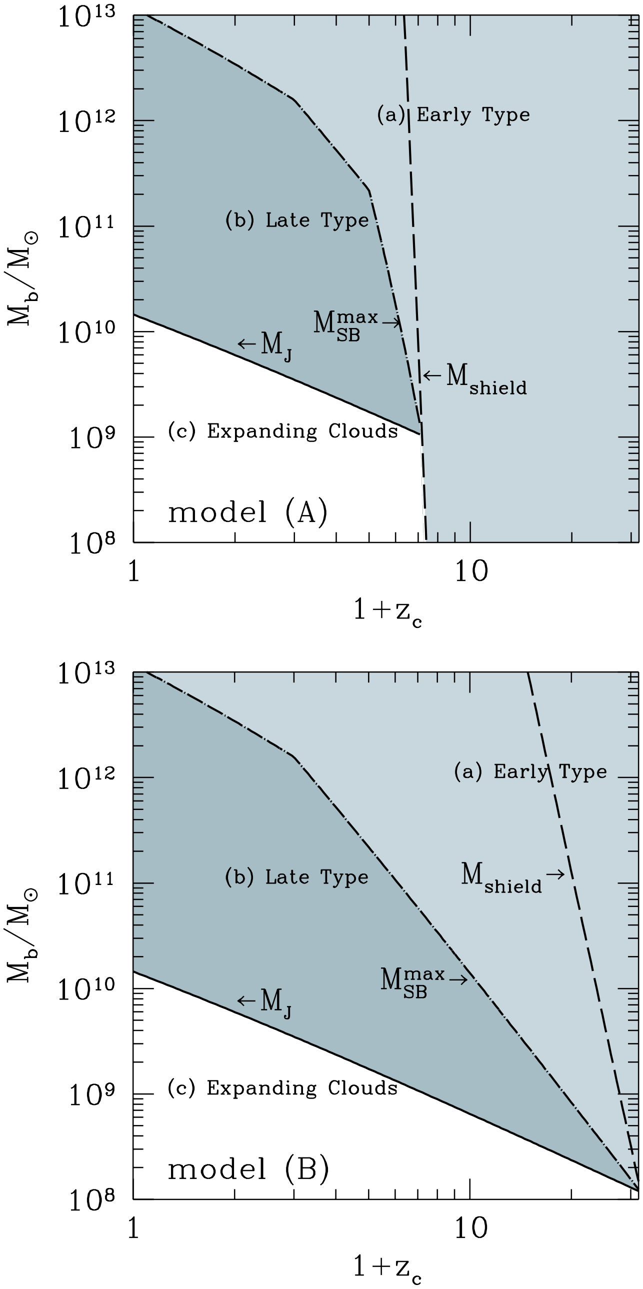

Figure 1. The bifurcation diagram. The prediction of galactic evolution is illustrated in the plane of baryonic mass (M_b) versus collapse redshift (z_c). The top panel corresponds to the ultraviolet evolution of model (A) (see text) and the bottom panel corresponds to that for model (B). In both of the panels the shaded area (a) denotes the region in which pre-galactic clouds evolve into early-type galaxies. The shaded area (b) leads to the formation of late-type galaxies. The unshaded area (c) represents the region in which the density perturbations cannot grow into bound objects owing to the thermal pressure of ionized gas. Here we employ $M_{\rm SB}^{\rm max}$ as the bifurcation mass, although the effect of dark matter may reduce the mass by a factor $(\Omega_b/\Omega)^{1.2}$ at most. $M_{\rm shield}$ denotes the mass above which the cloud is initially self-shielded.

with a large bulge-to-disc ratio (B/D) as a result of the dissipationless virialization. In region (b), the cloud is not self-shielded during the sheet collapse, but will be self-shielded in the course of the contraction to the rotation barrier. This leads to retarded star formation, and thus the virialization will proceed in a fairly dissipative fashion. As a result, a late-type (small B/D) galaxy is preferentially formed. Region (c) represents the forbidden region of the collapse owing to the Jeans stability.

SU have considered only the baryonic component, because, in the later collapsing phase, the cooling sheet is dominated by baryons, not by the diffuse dark matter. Then, if the ultraviolet background is constant, the bifurcation mass scale is given as

$$M_{\rm SB}^{\rm max} = 2.2 \times 10^{11}\,{\rm M}_\odot \left(\frac{1+z_{\rm c}}{5}\right)^{-4.2} \left(\frac{I_{21}}{0.5}\right)^{0.6}, \tag{1}$$

where I_{21} is the UV background intensity in units of $10^{-21}\,{\rm erg\,s^{-1}\,cm^{-2}\,sr^{-1}\,Hz^{-1}}$. However, the dark matter potential may affect the evolution in the early phase of collapse. If we take this effect into account maximally, the Jeans length is reduced by a factor of $\sqrt{\Omega_b/\Omega}$. With this Jeans scale, the bifurcation mass becomes $M_{\rm SB}^{\rm min} = (\Omega_b/\Omega)^{1.2} M_{\rm SB}^{\rm max}$. Thus the practical bifurcation mass will be between $M_{\rm SB}^{\rm max}$ and $M_{\rm SB}^{\rm min}$.

Also, SU have assumed the ultraviolet intensity to be independent of time. In practice, the intensity seems to evolve. Here we include the effect of the evolution of the ultraviolet background radiation. We assume $I_{21} = 0.5[(1+z)/3]^3$ for $z \leqslant 2$ and $I_{21} = 0.5$ for $2 \leqslant z \leqslant 4$. This dependence is consistent with the ultraviolet intensity in the present epoch (Maloney 1993; Dove & Shull), and the value inferred from QSO proximity effects at high redshifts (Bajtlik, Duncan & Ostriker 1988; Giallongo et al. 1996). As for $z > 4$, two extreme models are employed. The first one is (A) the exponentially damped model, $I_{21} = 0.5\exp[3(4-z)]$ (Umemura et al., in preparation), and the second one is (B) the constant extrapolation model, $I_{21} = 0.5$. In Fig. 1, these two extreme models are shown. The difference emerges particularly at $z_c \gtrsim 7$.

3 ESTIMATION OF GALACTIC MASSES AND COLLAPSE EPOCHS

Here, based upon observational data, we attempt to assess the total baryonic masses of ellipticals as well as spirals and their collapse epochs. Then, the observed galaxies are compared with theory in the bifurcation diagram.

To begin with, we evaluate the baryonic masses from *B*-band luminosities for ellipticals and from *I*-band luminosities for spirals with mass-to-light ratio $M_b = (M_*/L)L/f_*$, where M_* is the total stellar mass and f_* is the mass fraction of the stellar component in the total baryonic mass. The mass-to-light ratios M_*/L are obtained theoretically as well as observationally. Based on chemical evolution theory (Kodama & Arimoto 1997), M_*/L in the *B* band for ellipticals is 4–9. This value is consistent with observational estimates of 4–7 (Bertola et al. 1993; Pizzella et al. 1997). In this paper, we adopt the luminosity-dependent values given by Kodama & Arimoto (1997). M_*/L in the *I* band for spirals is 3.37 (Sa), 2.91 (Sb), 1.79 (Sc) and 1.33 (Sd) based on the code developed by Kodama & Arimoto (1997) with the S1 model of Arimoto, Yoshii, & Takahara (1992). These are also consistent with the observed data in Rubin et al. (1985). f_* is theoretically calculated by the population synthesis model to be 0.963 (Sa), 0.908 (Sb), 0.462 (Sc) and 0.125 (Sd), while basically $f_* = 1$ for ellipticals. With the estimated baryonic masses, we can determine the total masses as $M_{\rm tot} = M_b(\Omega/\Omega_b)$.

Next, we estimate the collapse epochs with the help of the virial theorem. For this purpose, we use the observed 1D velocity dispersion. We assume that the system is spherical and that the dark halo has isothermal distributions after virialization. We suppose a density perturbation of $\delta_i(r) = \bar{\delta}_i g(r)$, where r is the comoving radial coordinate and $g(r)$ is a function which is normalized as

$$\frac{3}{R^3}\int_0^R g(r) r^2\,\mathrm{d}r = 1,$$

with R being the comoving radius of the perturbed region. $\bar{\delta}_i$ is the spatially averaged $\delta_i(r)$ in the volume $r \leqslant R$. Summing up the initial kinetic energy and gravitational energy, we have the initial total energy of the perturbed region:

$$E_{\rm ini} = -\frac{3GM_{\rm tot}^2}{5R}(1+z_i)\bar{\delta}_i\left(1+\frac{2}{3}\phi\right)F, \tag{2}$$

where z_i is the initial redshift, ϕ is the contribution from the peculiar velocities, and $M_{\rm tot}$ is the total mass enclosed within the comoving radius R. The factor F is defined as

$$F \equiv \frac{5}{R^5}\int_0^R r^4 \bar{g}(r)\,\mathrm{d}r, \tag{3}$$

where

$$\bar{g}(r) \equiv \frac{3}{r^3}\int_0^r r'^2 g(r')\,\mathrm{d}r'.$$

In the linear regime, $g(r) \propto r^{1/(n+3)}$ around a density peak (Hoffman & Shaham 1985), where n denotes the index of the cold dark matter (CDM) power spectrum. Then equation (3) is readily integrated to give $F = 5/(2-n)$. We assume $n = -1$ throughout this paper, because it is the case for galactic scales in CDM cosmologies. The total energy of an observed galaxy is derived in terms of the virial theorem:

$$E_{\rm obs} = -\frac{3}{2}M_{\rm tot}\sigma_{\rm 1D}^2,$$

where $\sigma_{\rm 1D}$ is the 1D internal velocity dispersion of the galaxy. Assuming energy conservation, i.e. $E_{\rm int} = E_{\rm obs}$, we have

$$\frac{(1+z_i)\delta_i(1+2\phi/3)}{R} = \frac{5\sigma_{\rm 1D}^2}{2GM_{\rm tot}}F^{-1}. \tag{4}$$

On the other hand, the time when the outer boundary of a perturbation collapses is analytically obtained (Peebles 1993) as

$$t = \frac{\pi}{(GM_{\rm tot})^{1/2}}\left[\frac{R}{2(1+z_i)\delta_i(1+2\phi/3)}\right]^{3/2}. \tag{5}$$

Finally, using equations (4) and (5), we have the collapse epoch as

$$t = \pi G M_{\rm tot} F^{3/2}/5^{3/2}\sigma_{\rm 1D}^3.$$

By equating this time with the Hubble time $t_{\rm H}(z_{\rm c})$, t can be translated into the collapse redshift, $z_{\rm c}$. Thus it turns out that the velocity dispersion is a key quantity to determining $z_{\rm c}$. We use the observed stellar velocity dispersion as $\sigma_{\rm 1D}$ for elliptical galaxies. Also, for some luminous ellipticals, $\sigma_{\rm 1D}$ is estimated via the X-ray temperature $T_{\rm X}$ as $\sigma_{\rm 1D} = \sqrt{kT_{\rm X}/\mu m_{\rm p}}$. Estimation using X-rays gives typically twice the value estimated from the optical data, being probably the maximum determination of $\sigma_{\rm 1D}^2$. For spiral galaxies, we translate the asymptotic rotational velocity into the velocity dispersion by the relation $\sigma_{\rm 1D} = v_{\rm rot}/\sqrt{2}$.

The basic data on the luminosities and the velocity dispersions are taken from the table of Faber et al. (1989) for 332 ellipticals. The galaxies are selected from the original sample on the condition that the surface brightness, angular size and velocity dispersion are measured. The X-ray data for 12 ellipticals are adopted from the table in Matsumoto et al. (1997). Further, for 468 spiral galaxies, we combine the *I*-band luminosities from Mathewson & Ford (1996) and the asymptotic rotation velocities from Persic & Salucci (1995). We select the galaxies whose asymptotic velocities [$V_{\rm as}$ as in Persic & Salucci (1995)] are given. Thus the number of galaxies is smaller than the original number.

4 THEORY VERSUS OBSERVATIONS

In Fig. 2, the bifurcation theory is compared with observations. In this figure, the cosmological parameters are assumed to be $\Omega = 0.3$, $\Omega_\Lambda = 0$, $h = 0.7$ and $\Omega_{\rm b}h^2 = 0.02$. All of these values are plausible in the light of recent observations, although the value of the Λ-parameter is still controversial. The small filled triangles and open circles represent respectively the observed elliptical and spiral galaxies. The open star symbols are the X-ray-luminous elliptical galaxies. We find that the two types of galaxy are successfully divided by the theoretical bifurcation mass scale. This implies that self-shielding against the ultraviolet background radiation is related in practice to the origin of galactic morphology. The difference between models (A) and (B) is not so significant, although model (A) predicts a few more ellipticals than observed. Also, it is worth noting that few spiral galaxies reside above the bifurcation mass scale, whereas there are a noticeable number of elliptical galaxies that seem to have formed at lower redshift epochs than predicted by the present theory. Since a condition for constant velocity dispersion gives a relation

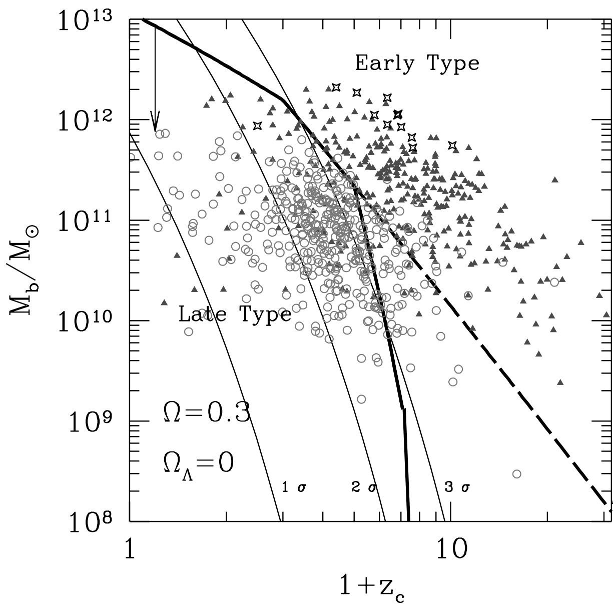

Figure 2. Comparison of observed galaxies with the bifurcation theory. Small open circles represent spiral galaxies from Persic & Salucci (1995). Small solid triangles denote the E and E–S0 galaxies from Faber et al. (1989). Open stars are elliptical galaxies from X-ray observations in Matsumoto et al. (1997). The thick solid and dashed lines represent the bifurcation mass $M_{\rm SB}^{\rm max}$ for models (A) and (B), respectively, where both are identical at $z_{\rm c} < 4$. The three thin solid lines marked as 1σ, 2σ and 3σ are the predictions in the CDM cosmology, where σ is the variance of CDM perturbations. The downward-pointing arrow in the upper-left corner of the figure shows the maximal shift of the bifurcation mass from $M_{\rm SB}^{\rm max}$ to $M_{\rm SB}^{\rm min}$ when including dark matter.

$M \propto (1+z)^{-3/2}$ in this diagram, most of the discrepant low-redshift ellipticals turn out to be relatively luminous galaxies with higher stellar velocity dispersions. Intriguingly, Gonzalez (1993) has reported, using strengths of Hβ and [MgFe] indices, evidence for intermediate-age populations in elliptical galaxies. In addition, it has been argued that galaxy mergers with burst-like star formation can lead to the formation of elliptical galaxies (Larson & Tinsley 1978; Barnes & Hernquist 1991, 1996; Kaufmann & Cahrlot 1998). Also, Shier & Fischer (1998) have suggested, by studying the stellar kinematics of starbursting infrared-luminous galaxies with obvious morphological signatures of a merger, that they can be progenitors of elliptical galaxies with high stellar velocity dispersions. Thus the discrepant low-redshift ellipticals might not be the results of primordial collapse, but could be a category of merger remnants.

In Fig. 2, 1σ, 2σ and 3σ CDM density perturbations normalized by *COBE* data (Hu & Sugiyama 1996; Bunn & White 1997) are also plotted. We find that elliptical galaxies form typically from $\sim 4\sigma$ perturbations and spirals form from $\sim 2\sigma$ peaks. If we change the cosmology, the results alter to some degree, because the bifurcation mass, the CDM spectra and the data points of elliptical and spiral galaxies are changed. The main change in Fig. 2 comes from changing Ω. The collapse epoch z_c for the observational data is dependent upon Ω as roughly $(1+z_c) \propto \Omega^{-0.74}$ for an $\Omega_\Lambda = 0$ universe. This dependence is mainly due to the evaluation of dark mass in a galaxy. For instance, if we employ $\Omega = 1$ (although it is unlikely), $1+z_c$ becomes almost 2.5 times smaller than the estimates in Fig. 2. In this case, the theory and the observational data seem perceptibly discrepant from each other. On the other hand, Fig. 2 is insensitive to the cosmological constant parameter Ω_Λ. In fact, even if we employ $\Omega = 0.3$ and $\Omega_\Lambda = 0.7$, the difference between the bifurcation mass and the observations remains almost unchanged, although the correspondence between CDM fluctuations and observations shifts from $\sim 4\sigma$ to $\sim 3\sigma$ for ellipticals. In this case, the theory is in good agreement with the observations. Further details of the dependences on the cosmological model will be discussed in a forthcoming paper.

The present results are also intriguing from the viewpoint of the statistics of galaxies. Bardeen et al. (1986) have shown that higher-σ peaks reside preferentially in denser regions rather than in low-density regions. As a result, the so-called density morphology relation can be explained as a natural consequence of the bifurcation theory. Furthermore, it is known that the specific angular momenta *J*/*M* of spirals are systematically greater by a factor of $\gtrsim 3$ than the *J*/*M* of ellipticals in the same mass range (Fall 1983). Based upon the tidal origin of the angular momentum, we expect $J/M \propto (1+z_c)^{-1/2}\nu^{-1}$, where $\nu \equiv \delta/\sigma$ (Heavens & Peacock 1988). If ellipticals form from $\sim 4\sigma$ peaks and spirals form from $\sim 2\sigma$ peaks, then we expect $(J/M)_{\rm spiral} \approx 3(J/M)_{\rm elliptical}$.

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