GALAXY FORMATION BY GALACTIC MAGNETIC FIELDS

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ABSTRACT

Galaxies exhibit a sequence of various morphological types, i.e., the Hubble sequence, and they are basically composed of spheroidal components (elliptical galaxies and bulges in spiral galaxies) and disks. It is known that spheroidal components are found only in relatively massive galaxies with \( M = 10^{10} - 10^{12} M_{\odot} \), and all stellar populations in them are very old, but there is no clear explanation for these facts. Here we present a speculative scenario for the origin of the Hubble sequence, in which the magnetic fields ubiquitously seen in galaxies have played a crucial role. We first start from a strange observational fact, that magnetic field strengths observed in spiral galaxies sharply concentrate at a few microgauss for a wide range of galaxy luminosities and types. We then argue that this fact and the observed correlation between star formation activity and magnetic field strength in spiral galaxies suggest that spheroidal galaxies have formed by starbursts induced by strong magnetic fields. Then we show that this idea naturally leads to the formation of spheroidal systems only in massive and high-redshift objects in a hierarchically clustering universe, giving a simple explanation for various observations.

Subject headings: cosmology: theory — galaxies: formation — galaxies: magnetic fields — stars: formation

1. INTRODUCTION

It is generally believed that the hierarchical structure seen today in the universe is generated by the gravitational instability of cold dark matter (CDM) whose density is about 10 times higher than that of baryonic matter, and then galaxies form in virialized dark matter halos by cooling of baryonic gas and subsequent star formation. The characteristic mass range of galaxies is about \( 10^{8} - 10^{12} M_{\odot} \), which can be understood as a mass range in which baryonic gas can cool sufficiently within a dark matter halo to form a galaxy (see, e.g., Blumenthal et al. 1984 for a review). However, spheroidal components reside only in relatively massive galaxies with \( M = 10^{10} - 10^{12} M_{\odot} \), and less massive galaxies are mostly irregular types or late-type spiral galaxies (Burstein et al. 1997; Hunter 1997). Elliptical galaxies and bulges appear to form a very uniform, old stellar population with very little scatter in metallicity and star formation history, and they are generally considered to have formed by intensive starbursts at high redshifts (e.g., Renzini 1999).

The trigger mechanism for starbursts is unknown, and it is often assumed to be mergers of disk galaxies when galaxy formation is modeled in the context of hierarchical structure formation in the CDM universe (Kauffmann, White, & Guiderdoni 1993; Baugh, Cole, & Frenk 1996). However, there is no evidence for spheroidal galaxy formation through mergers, and the merger hypothesis does not give a clear explanation for the fact that all spheroidal systems are very old and only in massive galaxies. These trends appear to run opposite to the expectation of structure formation in the CDM universe, in which smaller objects form earlier and then massive objects later. This is currently considered as a major challenge for galaxy formation in the CDM universe (e.g., Renzini 1999), and it is interesting to seek a mechanism that triggers starbursts only in massive and high-redshift objects. In this Letter, we show that a possible strong dependence of star formation activity on magnetic field strengths, which is suggested by observations of magnetic fields in local galaxies, gives a candidate for such a mechanism.

2. GALACTIC MAGNETIC FIELDS AND STAR FORMATION ACTIVITY

Interstellar magnetic fields in galaxies are strong enough to significantly affect interstellar gas dynamics on both global scales characteristic of galactic structure and small scales characteristic of star formation (see, e.g., Vallée 1997; see Zweibel & Heiles 1997 for a review). Fitt & Alexander (1993, hereafter FA) derived strengths of volume-averaged magnetic fields for 146 spiral galaxies, which is a complete sample including various types from Sa to irregular galaxies, and they found a strange result: the dispersion in strength is surprisingly narrow—within a factor of less than 2 with an average strength of \( 3 \mu G \)—in spite of a wide range of absolute radio luminosities of galaxies (almost 4 orders of magnitude). Why is magnetic field strength so uniform at \( \sim 3 \mu G \) for various types of galaxies with such a wide range of luminosities? Clearly there should be a physical reason for this strange fact.

Vallée (1994) investigated the relation between the magnetic field strength and star formation activity by using 48 galaxies out of the FA sample and found that there is a correlation between magnetic field strength \( (B) \) and star formation efficiency \( (SFE) \): \( B \propto (SFE)^i \), with \( i = 0.13 \pm 0.04 \). (The same relation was also found for star formation rate \( (SFR) \) and \( B \).) From this result, one may conclude that star formation activity does not strongly affect the strength of magnetic fields. However, it is also likely that star formation rate \( (SFE) \) is affected by magnetic fields. If we take the result of Vallée in this context, the observed correlation suggests that star formation activity depends quite sensitively on \( B \) as \( SFE \propto B^q \), with \( q = 1/\ell_1 \sim 7.7 \pm 2.6 \). Here we point out that, if this is the case, the surprisingly narrow dispersion in galactic magnetic fields is naturally explained by an observational selection effect. If the strength of magnetic fields in an object is significantly smaller than a few microgauss, the star formation activity becomes much lower than in typical spiral galaxies, and the object cannot produce enough stars to be observed as a galaxy. On the other hand, if magnetic fields are stronger than a few microgauss,
such objects would experience strong starbursts and all interstellar gas will be converted into stars. If the star formation timescale is shorter than the dynamical timescale for disk formation, they will become present-day spheroidal systems. Magnetic fields in elliptical galaxies are difficult to measure since there are no relativistic electrons to illuminate the magnetic fields by synchrotron radiation. Then the reason that the observed dispersion of magnetic fields is quite small can be understood by an observational selection effect; we cannot observe or measure magnetic field strength when the strength is significantly different from the typically observed value of $\sim 3 \mu G$.

Therefore, the observed correlation between $B$ and SFE, as well as the surprisingly narrow dispersion of the measured values of magnetic field strength, well suggests a strong dependence of star formation activity on magnetic field strength. This idea is further supported by an amorphous spiral galaxy M82, which has an abnormally large magnetic field of $\sim 10 \mu G$ in the sample of FA. M82 is actually known as an archetypal starburst galaxy, and the strong field strength suggested by FA is caused by the very strong field ($\sim 50 \mu G$) in the nuclear region of this galaxy, in which intense star formation is underway (Klein, Wielebinski, & Morsi 1988; Vallée 1995a). Unfortunately, our knowledge of the physics of star formation is poor, and it is not clear from a theoretical point of view why SFE depends so strongly on $B$, but it is not unreasonable. In fact, at least one effect is known by which magnetic fields help star formation: magnetic braking (e.g., McKee et al. 1993 for a review). In order for a protostellar gas cloud to collapse into stars, a significant amount of initial angular momentum must be transported outward. Magnetic fields play an important role for this angular momentum loss by Alfvén waves launched into the ambient medium. Strongly magnetized objects with large-scale high gas density would be followed by magnetic braking of individual regions with angular momentum losses, ending in outgoing Alfvén waves, gas collapse, and star formation on a large scale.

It should be noted that the above hypothesis does not contradict the well-known Schmidt law of star formation. Vallée (1995b, 1997) found a relation between magnetic field strength and interstellar gas density on a scale of a whole galaxy as $B \propto n^4$, with $k = 0.17 \pm 0.03$. By using this relation and the $B$-SFR relation, we find SFR $\propto n^{13/4}$, with $k/\ell = 1.3 \pm 0.1$. This relation agrees well (Vallée 1997) with some direct estimates of the relation between SFR and $n$ (e.g., Kennicutt 1989; Shore & Ferrini 1995; Niklas & Beck 1997). At the same time, these relations suggest that the thermal energy of interstellar matter is not in equipartition with the magnetic field energy or cosmic-ray energy (Kamaya 1996). It is possible that what is physically affected by magnetic fields is gas density, and then the gas density determines the SFE by the Schmidt law, producing the observed $B$-SFE relation.

Anyway, the correlation between $B$ and SFE has actually been observed, and it is natural to assume that this relation also holds in high-redshift objects. (The chance probability of observing such a correlation from an uncorrelated parent population is only 12%; Vallée 1994.) Therefore, the following analysis is valid unless some unknown processes violate this empirical relation in high-redshift objects.

### 3. MAGNETIC FIELDS IN HIERARCHICAL STRUCTURE FORMATION

As discussed above, it is suggested that spheroidal components of galaxies formed by starbursts that were induced by strong magnetic fields. In the following, we consider magnetic field generation and formation of spheroidal systems in the framework of the standard cosmological structure formation in the CDM universe and show that spheroidal systems form only in relatively massive objects at high redshifts. Recently it has been discussed that galactic magnetic fields are generated at the stage of protogalactic cloud collapse (Kulsrud et al. 1997).

Although there are some other scenarios for the origin of galactic magnetic fields, such as earlier field generation on cosmological scales or dynamo amplification after galaxies form (see, e.g., Zweibel & Heiles 1997), we assume here that magnetic fields are generated during the collapse of protogalactic clouds. When a dark matter halo decouples from the expansion of the universe and collapses into a virialized object, the gravitational energy of baryonic gas is converted into turbulent motions and thermal energy by generated shocks. It can be shown that a very weak magnetic field ($\sim 10^{-21} G$), which has been generated by thermoelectric current before collapse (i.e., the battery mechanism), is amplified up to a strength nearly in equipartition with turbulent energy (Kulsrud & Anderson 1992; Kulsrud et al. 1997). The timescale for equipartition is given by $t_{\nu\nu}$, where $\nu$ is the length scale of the system and $v$ is the turbulent velocity. If we take the radius and three-dimensional velocity dispersion of a virialized halo as $r$ and $v$, it is straightforward to see that this timescale is given by the dynamical timescale of the halo. Then we can estimate the strength of magnetic fields by the turbulent energy density of baryonic gas in a collapsed object, which is determined by using the well-known spherical collapse model (e.g., Peebles 1980). For a dark halo with mass $M_h$ and formation redshift $z$, the turbulent energy density becomes $\epsilon_\nu \sim (3 \Omega_0 M_{h,7}^2 / 8 \pi \Omega_\nu r^3) = 6.4 \times 10^{-11} h^{10/3}{M_{h,7}^2/(1+z) \Omega_\nu} \text{ergs cm}^{-3}$, where $h$ is the Hubble constant normalized at 100 km s$^{-1}$ Mpc$^{-1}$, $M_h = M_{h,12}(10^{12} M_\odot)$, and $\Omega_\nu$ and $\Omega_\nu$ are the baryon and matter density in units of the critical density in the universe. In the second expression above, we have assumed the Einstein–de Sitter universe ($\Omega_\nu = 1$), but extension to other cosmological models is easy. According to the theory of Kulsrud & Anderson (1992), we assume that one-sixth of the turbulent energy is converted into magnetic field energy, and then the equipartition magnetic field becomes $B \sim 1.6 h^{10/3}{M_{h,7}^{1/2}(1+z)^2 \Omega_\nu^{1/2}} \mu G$. The observational properties of disk galaxies including our Galaxy are well understood if they are considered to have formed at $z \sim 0–1$ (Mao & Mo 1998), and hence this theory of magnetic field generation gives a roughly correct strength for our Galaxy with $M_h \sim 10^2 M_\odot$.

### 4. EMERGENCE OF THE HUBBLE SEQUENCE

According to the above arguments, spheroidal galaxies are expected to form at high redshifts in massive dark matter halos because magnetic fields become stronger with increasing mass and redshift as $B \propto M_h^{1/3}(1+z)^2$. In order to discuss this more quantitatively, we equate the previously defined star formation efficiency (in § 2) to $\epsilon_* = (t_{\nu\nu})^{-1}$, where $t_{\nu\nu}$ is the timescale on which interstellar gas is converted into stars. The star formation rate $M_*$ in a galaxy is given by $M_* = M_{gas} / t_{\nu\nu}$, where $M_{gas}$ is the mass of interstellar gas in the galaxy. As mentioned earlier, the observed relation between $B$ and $v$ is $v \propto B^q$, with $q \sim 7.7 \pm 2.6$. We set the normalization of this relation by SFE at our Galaxy. The star formation rate in our Galaxy is about $7.7 \pm 2.6$. The essence of this result can be understood by a dimensional analysis. The equation of magnetic field generation is $dB/dt = \nabla \times (v \times B)$, where $v$ is the velocity field of fluid, and when we estimate $\nabla \times$ by the inverse of the system scale, it is clear that the field evolution timescale is given by $t_{\nu\nu}$. 

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few $M_\odot$ yr$^{-1}$ and the mass of the interstellar gas in the disk is about $6 \times 10^8 M_\odot$ at present, suggesting that $t_{\text{dyn}} \sim 2$ Gyr at $B \sim 3 \mu$G (e.g., Binney & Tremaine 1987). We also normalize the strength of $B$ to $3 \mu$G for a halo whose baryonic mass is $6 \times 10^{10} M_\odot$ and whose virialization occurred at $z = 1$, supposing our Galaxy. Then we can calculate the ratio of baryonic dynamical time to $t_{\text{dyn}}$, $\Gamma = t_{\text{dyn}}/t_{\text{vir}}$, which can be considered as a criterion for spheroidal formation. In calculating $t_{\text{dyn}}$, we use a baryon density $\rho_0$ times higher than the value at virialization, considering the contraction of baryons due to cooling and dissipation, where $\rho_0 \sim 0.05$ is the typical dimensionless angular momentum of dark halos (Warren et al. 1992). If $\Gamma \gg 1$, spheroidal systems are expected to form.

In Figure 1, we have plotted the contours of $\Gamma = 1, 10, \text{and } 100$ by thin solid lines in the plane of the baryon mass of a collapsed object ($M_{\text{baryon}}$) and its formation redshift, assuming $q = 5$. (The observed mass of galaxies is considered to be mainly baryonic mass.) For reference, we have also plotted the contour of magnetic field strengths in Figure 2. We have used a flat, $\Lambda$-dominated cosmological model in which $\Lambda$ is the cosmological constant, with the standard cosmological parameters of $(h, \Omega_{m}, \Omega_{\Lambda}, \sigma_8) = (0.7, 0.3, 0.7, 1)$. This universe is quite consistent with various observations such as the ages of globular clusters, high-redshift Type Ia supernovae (Perlmutter et al. 1998), the cosmic microwave background (Bunn & White 1997), and the abundance of clusters of galaxies (Kitayama & Suto 1997). In the following, we discuss the emergence of the Hubble sequence using Figure 1. Objects lying above the thin solid lines are expected to form spheroidal galaxies, but we have to check how such objects are typical in the context of cosmological structure formation in the CDM universe. For this purpose, we have plotted the mass scale of the $n$-$\sigma$ fluctuation as defined in Blumenthal et al. (1984) by dashed lines. The lines are defined by $\sigma(M_\odot, z) = \delta_0$, where $\sigma(M_\odot, z)$ is the rms of density fluctuation predicted by linear theory in the CDM universe at a scale of $M_\odot$ and at redshift $z$ (Peacock & Dodds 1994; Sugiyama 1995), and $\delta_0 \sim 1.69$ is a critical density contrast at which an object virializes (Peebles 1980). The three dashed lines correspond to $n = 1, 2, \text{and } 3$, and these lines represent typical mass scales of collapsed objects as a function of $z$. (For larger $n$, the cosmological abundance of objects is statistically suppressed as $\propto e^{-\delta_0^2}$.) In the region in which the dashed lines are above the solid lines, spheroidal galaxies can form as cosmologically typical objects. Figure 1 shows that objects with $M_{\text{baryon}} \approx 10^8$ to $10^{10} M_\odot$, with $\sim 2-3 \sigma$ fluctuations will form spheroidal systems because $\Gamma \gg 1$, at high redshifts of $z \sim 3-10$ with $B \sim 50 \mu$G (see also Fig. 2). It is interesting to note that this magnetic field strength is roughly the same as that in the starbursting nucleus of M82, as mentioned in § 2. Spheroidal formation with $M_{\text{baryon}} \approx 10^8$ to $10^{10} M_\odot$ is inhibited because of low $\Gamma$ for cosmologically typical objects. On the other hand, if $M_{\text{baryon}}$ is larger than $\sim 10^{12} M_\odot$, the formation of galaxies is inhibited by a cooling time that is too long ($t_{\text{cool}}$) compared to the Hubble time at each redshift ($t_H$), as shown by the dotted lines, which are contours of $t_{\text{cool}}/t_H$ (Blumenthal et al. 1984). Therefore, our model can explain the observed mass range ($10^8$ to $10^{12} M_\odot$) and old stellar populations seen in spheroidal galaxies. The region for spheroidal galaxy formation is schematically indicated in Figures 1 and 2 by the thick solid line. After spheroidal galaxy formation, gas accretion onto some of them is possible at lower redshifts. Since such gas accreting recently is located below the thin solid lines in Figure 1, it results in disk formation of spiral galaxies at $z \approx 1$. On the other hand, if recent gas accretion is negligible, such objects will be seen as present-day elliptical galaxies.

Since the solid lines (constant $\Gamma$) and the dashed lines ($n$-$\sigma$ lines) are approximately parallel in the region of spheroidal formation, our scenario for the origin of the Hubble sequence...
predicts that elliptical galaxies should lie on a constant $n$-$\sigma$ density fluctuation with $n \sim 2-3$, and with decreasing $n$, the type of galaxies becomes later in the Hubble sequence, i.e., from early to late spiral, and then into irregular galaxies at $\sim 1$ $\sigma$ fluctuation. In fact, this trend is exactly what has been observed in galaxies (Blumenthal et al. 1984; Burstein et al. 1997), giving further support for our scenario. Most properties or relations observed in present-day galaxies—such as the Tully-Fisher or the Faber-Jackson relation and the existence of the fundamental plane for galaxies and their distribution on it—can be explained by formation of early-type galaxies from higher $n$-$\sigma$ fluctuations than later Hubble types (Burstein et al. 1997). The density-morphology relation, which is the correlation between galaxy types and number density, is also explained; higher $n$-$\sigma$ fluctuations occur preferentially in denser regions destined to become rich clusters, and hence one expects to find more elliptical galaxies there, as is observed (Blumenthal et al. 1984). Higher $n$-$\sigma$ objects are expected to show stronger spatial clustering than lower ones (e.g., Mo & White 1996), and it is consistent with the stronger clustering observed for elliptical galaxies than for late-type galaxies (Loveday et al. 1995). Various observations suggest that giant galaxies formed at higher redshifts of $z \gtrsim 3$ and were then followed by a sequence of less and less massive galaxies forming at lower and lower redshifts, leading down to the formation of dwarfs at recent ($z \approx 0.5$) (Fukugita, Hogan & Peebles 1996; Sawicki, Lin, & Yee 1997). The proposed scenario gives an explanation for this trend, which is sometimes termed “downsizing”; otherwise, it seems to oppose the expectation in the CDM universe.

5. DISCUSSION AND CONCLUSIONS

For very low mass objects, star formation is strongly suppressed by the absence of physical triggers when magnetic fields are weak, and this may give an explanation for the fact that the faint end of the luminosity function of galaxies is much flatter than expected from the mass function of dark halos (Kauffmann et al. 1993; Baugh et al. 1996). Because of the strong dependence of star formation activity on magnetic fields, the stellar luminosity of galaxies would quite rapidly decrease with decreasing galaxy mass. Then it is expected that, in the faint end of the galaxy luminosity function, the mass of galaxies does not change much compared to the change in luminosity. Since the number density of objects is determined by the mass of objects, the faint end is expected to be relatively flat, as observed. Irregular galaxies or late-type galaxies are expected to show a wide range of star formation activity within a narrow range of galaxy masses depending on the magnetic field strength in them, and in fact such a trend has been observed (Hunter 1997).

It is well known that galaxy interactions or mergers induce intensive starbursts, but the mechanism that triggers starbursts in galaxy interactions is still poorly known. Mergers are followed by cloud collisions, which lead to high gas density, strong turbulences, and strong magnetic fields and which end in gas collapse and star formation in clouds. Therefore, the hypothesis presented in this Letter, i.e., that star formation activity strongly depends on magnetic field strengths, may also be important in the merger-induced starbursts. Some fraction of elliptical galaxies may have formed by such a process, but we have argued that the observed trends of elliptical galaxies, i.e., being massive and old, originate mainly from properties of gravitationally bound objects in the standard theory of cosmological structure formation.

We have presented a new idea for the origin of the Hubble sequence of galaxies. The key of this scenario is the strong dependence of star formation activity on average magnetic fields in galaxies, which is just a speculation from a theoretical point of view but is motivated by several observational facts about magnetic fields in nearby galaxies. This single speculation provides a simple explanation for the surprisingly narrow dispersion in the magnetic field strengths observed in spiral galaxies and also for most properties of galaxies seen along the Hubble sequence. To verify this “magnetic galaxy formation” scenario as the origin of the Hubble sequence, it is indispensable to confirm observationally that starbursts are actually triggered by stronger magnetic fields. Comprehensive measurements of galactic magnetic fields in larger samples of galaxies are necessary, especially for starburst galaxies at local as well as at high redshifts.

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