POTENTIAL FORMATION SITES OF SUPER–STAR CLUSTERS IN ULTRALUMINOUS INFRARED GALAXIES

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ABSTRACT

Recent observational results on high spatial resolution images of ultraluminous infrared galaxies (ULIGs) have revealed very luminous, young, compact, and heavily obscured super–star clusters in their central regions, suggested to be formed by gas-rich major mergers. By using stellar and gaseous numerical simulations of galaxy mergers, we first demonstrate that the central regions of ULIGs are the most promising formation sites of super–star clusters owing to the rather high gaseous pressure of the interstellar medium. Based on simple analytical arguments, we then discuss the possibility that super–star clusters in a ULIG can be efficiently transferred into the nuclear region owing to dynamical friction and consequently merge with one another to form a single compact stellar nucleus with a seed massive black hole. We thus suggest that multiple merging between super–star clusters formed by nuclear starbursts in the central regions of ULIGs can result in the formation of massive black holes.

Subject headings: galaxies: active — galaxies: interactions — galaxies: kinematics and dynamics

1. INTRODUCTION

Recent high-resolution imaging by Hubble Space Telescope (HST) has revealed super–star clusters (SSCs) with masses of $10^5$–$10^6 M_\odot$, very young ages, and large dust extinction in ultraluminous infrared galaxies (ULIGs), most of which are ongoing mergers (e.g., Shaya et al. 1994; Surace et al. 1998; Surace & Sanders 1999; Scoville et al. 2000). These SSCs are frequently observed not only in merging galaxies with and without ultraluminous infrared activity (e.g., in the Antenna by Whitmore et al. 1999) but also in starburst galaxies such as M82 (e.g., de Grijs, O’Connell, & Gallagher 2001), which implies that the presence of SSCs is a generic feature in intensively starbursting or merging galaxies such as ULIGs (Lutz 1991; Ashman & Zepf 1992; Surace & Sanders 1999). These discoveries of SSCs in ULIGs have raised the following three questions (e.g., Shaya et al. 1994; Forbes, Brodie, & Grillmair 1997; McLaughlin 1999; Larsen & Richtler 2000): (1) What is the dominant mechanism of SSC formation? (2) How can the global dynamics of merging galaxies be associated with the SSC formation? (3) Is the formation efficiency of SSCs different between merging galaxies and normal spiral galaxies?

The purpose of this Letter is to investigate the formation and dynamical evolution of SSCs in ULIGs formed by gas-rich major mergers and thereby to try and provide some plausible answers for the above three questions. In particular, we adopt the plausible assumption that the rather high pressure of the warm interstellar gas ($P > 10^4 k_B$; $k_B$ is Boltzmann’s constant) can induce global collapse of giant molecular clouds to form massive compact star clusters corresponding to SSCs (Jog & Solomon 1992; Harris & Pudritz 1994; Elmegreen & Efremov 1997). Accordingly, we investigate numerically the time evolution of gaseous pressure in gas-rich mergers with different merger parameters. Previous theoretical results have already demonstrated that if a compact stellar system has a very large number of stellar-mass black holes left after the normal processes of stellar evolution (in massive stars), these black holes can evolve into a single massive black hole (e.g., Quinlan & Shapiro 1989; Lee 1995). Based on simple analytic arguments, we suggest that SSCs formed in a ULIG can be transformed into a compact self-gravitating stellar system (i.e., a considerably large SSC) either with a few tens of massive black holes (MBHs) with masses ranging from $10^4$ to $10^6 M_\odot$ or with $10^5$–$10^6$ stellar-mass black holes. Thus, the present numerical results combined with analytical ones suggest that the dynamical evolution of SSCs in the central regions of ULIGs can be closely associated with the formation of supermassive black holes.

2. MODEL

Our numerical methods for modeling chemodynamical evolution of dusty starbursts associated with galaxy mergers have already been described by Bekki & Shioya (1998). Furthermore, the details of the adopted TREESPH, which is based on that used in early numerical works (e.g., Heller & Shlosman 1994), are given by Bekki (1995). We accordingly give these numerical techniques only a brief review here. We construct models of galaxy mergers between gas-rich disks by using the model of Fall & Efstathiou (1980). The total mass and the size of a progenitor exponential disk are $M_d$ and $R_d$, respectively. From now on, all the masses and lengths are measured in units of $M_d$ and $R_d$, respectively, unless otherwise specified. Velocity and time are measured in units of $v = (G M_d / R_d)^{1/2}$ and $t_{dyn} = (R_d / G M_d)^{1/2}$, respectively, where $G$ is the gravitational constant and assumed to be 1.0 in the present study. If we adopt $M_d = 6.0 \times 10^{10} M_\odot$ and $R_d = 17.5$ kpc as fiducial values, then $v = 1.21 \times 10^3$ km s$^{-1}$ and $t_{dyn} = 1.41 \times 10^9$ yr, respectively. The dark–to–disk halo mass ratio and the star-to-gas mass ratio are set equal to 4.0 and 9.0, respectively. The bulge component is not included in the present study. An isothermal equation of state is used for the gas with a temperature of $7.3 \times 10^3$ K (corresponding to a sound speed of 10 km s$^{-1}$). The initial metallicity, $Z_*$, for each gaseous particle in a given galactic radius $R$ (in kiloparsecs) from the center of a disk is given according to the observed relation $Z_* = 0.06 \times 10^{-0.197 R / 0.355}$ of typical late-type disk galaxies (e.g., Zaritsky, Kennicutt, & Huchra 1994). We present the results mostly for merger models with nearly prograde-prograde orbital configurations, parabolic encounters, and a pericentric distance of 0.5$R_d$. We change the mass ratio ($m_2$) of the two merging disks and thereby investigate the dependence of SSC formation processes on $m_2$ over the range 0.1 (corresponding to minor merging) $\leq m_2 \leq 1.0$ (major). For comparison, we also show the results of an isolated disk model and a tidally interacting one (in which two galaxies do not merge with each other owing
to the large pericentric radius of $2R_p$ adopted for the parabolic orbit). Total particle number in each simulation is 23,178 for the collisionless components and 20,000 for the collisional ones.

We adopt the following two different star formation laws and thereby convert the gaseous components into collisionless new stellar particles. In the first law, we adopt the formation model for SSCs (globular clusters) of Harris & Pudritz (1994) in which interstellar gaseous pressure ($P_g$) in star-forming regions of a galaxy can drive pressure-confined, magnetized self-gravitating protocluster molecular clouds to collapse to form SSCs if $P_g$ is larger than the surface pressure ($P_s$) of the clouds:

$$P_g \geq P_s \approx 2.0 \times 10^3 \text{k}_\text{B}.$$  

In the simulations, a gas particle becomes one new SSC if the particle’s pressure is larger than $P_s = 2.0 \times 10^3 \text{k}_\text{B}$. Although we cannot investigate the detailed physical processes of SSC formation in the present global (from $\sim$100 pc to 10 kpc scale) simulation, the adopted phenomenological approach of SSC formation enables us to trace at least the most promising formation sites of SSCs in an admittedly plausible way. The other is the Schmidt law (Schmidt 1959) with the exponent of 1.5 (Kennicutt 1989), and newly formed stars due to the Schmidt law are referred to as “normal stars” (NSs) for convenience. If both conditions are satisfied above, only SSC is assumed to be formed. The effects of radiative cooling and those of supernova feedback effects on SSC formation will be explored in our future papers. Furthermore, if $P_s = 2.0 \times 10^3 \text{k}_\text{B}$, the formation efficiency is $\sim$6 times smaller.

3. RESULTS

Figure 1 clearly demonstrates how the gaseous pressure of the interstellar medium becomes dramatically higher ($10^4 \text{k}_\text{B}$–$10^5 \text{k}_\text{B}$) in some regions of the major merger model with $m_2 = 1.0$ at $T = 0.28$ Gyr (starburst phase with the star formation rate of $\sim$75 $M_\odot$ yr$^{-1}$) in comparison with the initial disks. Furthermore, gaseous pressure for some fraction of the gas particles (in particular, in the central regions) exceeds the threshold value of $2.0 \times 10^3 \text{k}_\text{B}$ for SSC formation, essentially because rapid transfer of gas to the central region of the merger and efficient gaseous shock dissipation increase the gaseous density and pressure greatly. These results clearly explain the reason why SSCs can be formed in ULIGs and imply that the formation efficiency of SSCs are much higher in merging galaxies with massive starbursts than in “normal” disk galaxies. Figure 2 shows that SSCs are formed not only in the central region, where gas fueling is more efficient, but also in the outer tidal tails and “bridges” among the two cores, where the tidal force of the merger forms thin and high-density gaseous layers owing to gaseous shock dissipation. This result is qualitatively consistent with recent HST observational results that SSCs are located both in the central regions (e.g., Arp 220; Shaya et al. 1994) and between the two merging cores (e.g., VV 114; Scoville et al. 2000) of ULIG mergers.

As is shown in Figure 3, the peak metallicity in the metallicity distribution of SSCs is fairly high (0.05 corresponding to a 2.5 solar value and a factor of 2 higher than metal-rich globular clusters in elliptical galaxies), first because the initial mean metallicity of the merger precursor disk is assumed to be also high (1.4 solar) and, second, because chemical enrich-
Fig. 2.—Mass distribution projected onto the x-y plane in the merger model with \( m_1 = 1.0 \) at \( T = 0.28 \) Gyr for all components (top) and for SSCs (bottom). In total, 2667 SSCs have been already formed prior to this starburst epoch (with the star formation rate of \( \sim 75 \, \text{yr}^{-1} \)). The scale is given in our units (17.5 kpc), and each of the frames measures 70 kpc on a side.

In major mergers than in tidally interacting galaxies imply that major mergers, which more dramatically transform galactic morphologies than tidally interacting ones (e.g., M82), provide the most promising formation sites of SSCs.

4. DISCUSSION AND CONCLUSION

One of the most long-standing and remarkable problems in the formation and evolution of ULIGs is whether there is an evolutionary link between the two different types of nuclear activities—starbursts and active galactic nuclei (e.g., Sanders & Mirabel 1996). Previous theoretical studies have attempted to understand either physical mechanisms for the efficient radial transfer of gas to the nuclear starburst regions in major mergers (e.g., Barnes & Hernquist 1992; Mihos & Hernquist 1996) or the growth process of the already existing seed MBHs (with masses of \( \sim 10^6 \, M_\odot \); Norman & Scoville 1988). We discuss here this problem in the context of how a cluster of SSCs in the circumnuclear region of a ULIG evolves dynamically into a seed MBH. We suggest that the following timescale of dynamical friction (Binney & Tremaine 1987) is important for discussing this problem of SSC evolution:

\[
t_{\text{dynamical}} = 3.9 \times 10^8 \left( \frac{r_i}{500 \, \text{pc}} \right)^2 \frac{V_c}{400 \, \text{km s}^{-1}} \frac{10^7 \, M_\odot}{M_1} \, \text{yr}.
\]

Here we neglect the \( \ln \Lambda \) term (\( \sim 6.6 \) for a plausible set of parameters), \( r_i \), \( V_c \), and \( M_1 \) are the initial radius (from the center of a ULIG), circular velocity, and mass of the SSC, respectively. This timescale argument implies that SSCs formed by dusty starbursts in major mergers can sink into the central 10–30 pc region and consequently merge with one another to form a single massive nuclear SSC within a few dynamical timescales of the ULIG (i.e., \( \sim 10^8 \) yr). We here point out that the fate of SSCs depends strongly on whether or not these are
tidally disrupted in merging galaxies; it is also possible that SSCs are disrupted by the central strong tidal field of ULIGs before they reach the central few parsecs in ULIGs. However, recent observational (e.g., Okuda et al. 1990; Nagata et al. 1995) and theoretical (e.g., Portegies Zwart et al. 2001) results demonstrated that the central region of the Galaxy can easily harbor compact star clusters (corresponding to SSCs). Although dynamical conditions could be different between the central region of the Galaxy and those of mergers, these results on the Galactic SSCs imply that SSCs in ULIGs can also survive from tidal disruption owing to their compact nature and consequently reach the central few parsecs via dynamical friction.

A high-density compact stellar system has been demonstrated to form a single MBH as a result of the coalescence of stellar-mass black holes or neutron stars left after the normal processes of stellar evolution, within the dynamical relaxation timescale of \( t_{\text{rel}} \) (e.g., Lee 1995). Therefore, if the central region of a ULIG has \( \sim 10^5 \) SSCs with typical mass \( 10^6 \) \( M_\odot \) and if \( t_{\text{merger}} > t_{\text{rel}} \), a single very massive nuclear cluster with \( \sim 10^7 \) \( M_\odot \) can be formed after the merging of the SSCs. Furthermore, these MBHs in the cluster may well sink into the central subparsec region as a result of dynamical friction and consequently form a self-gravitating MBH cluster. Although it could be possible that multiple merging of these MBHs through gravitational radiation loss in this MBH cluster can form a single MBH, the evolution of such multiple MBH interaction is obviously beyond the scope of this Letter (see more detailed discussions in Valtonen et al. 1994 and Xu & Ostriker 1994). On the other hand, if \( t_{\text{merger}} < t_{\text{rel}} \) then a single massive cluster with huge number of \( (\sim 10^5) \) stellar-mass black holes can be formed. In this case also, successive merging of these black holes in a cluster can drive the formation of a single supermassive black hole within the Hubble time if both the density and the velocity dispersion of the cluster are rather high (Quinlan & Shapiro 1989). Although these discussions are highly speculative, in each case, it seems to be inevitable that a central supermassive black hole forms as a natural result of dynamical evolutions of SSCs in the nuclear region of a ULIG.

Recent dynamical studies based on \( HST \) photometry and ground-based spectroscopy of the central bulge regions of 36 nearby galaxies demonstrated that the nuclear MBH (or massive dark object) to bulge mass ratio \( (f_{\text{BH}}) \) is \( \sim 0.006 \) (Magorrian et al. 1998). If we adopt the assumption that most giant elliptical galaxies and bulges are formed by gas-rich major mergers (e.g., Toomre 1977) and successors of ULIGs (e.g., Sanders et al. 1988), we can discuss whether the MBH formation due to merging of SSCs in ULIGs is consistent with the observed \( f_{\text{BH}} \) value. For a spherical galaxy formed by merging, 

\[
f_{\text{BH}} = f_{\text{g}} f_{\text{sf}} f_{\text{ssc}} f_{\text{sh}},
\]

where \( f_{\text{g}}, f_{\text{sf}}, f_{\text{ssc}}, \) and \( f_{\text{sh}} \) are the gas mass fraction, the mass ratio of new stars formed during merging (including SSCs) to gas mass, that of SSCs to the total mass of new stars, and that of the total mass of stellar-mass black holes to the total mass of an SSC. If we adopt a set of plausible values—\( f_{\text{g}} = 0.2 \) (from the typical value observed for late-type spiral galaxies), \( f_{\text{sf}} = 0.8 \) (from the present study), \( f_{\text{ssc}} = 0.2 \) (Shioya et al. 2001), and \( f_{\text{sh}} = 0.1 \) (Norman & Scoville 1988)—then \( f_{\text{BH}} = 0.0032 \), which is similar to the value observed. The most important point in the above estimation is that the origin of \( f_{\text{BH}} \) can be closely associated with the formation efficiency of SSCs in ULIGs \( (f_{\text{ssc}}) \), which has not been pointed out by previous studies. Finally, we suggest that the origin of the physical relationship between the masses of MBHs and those of galactic spheroids (e.g., Magorrian et al. 1998) can be understood in terms of the formation and evolution of SSCs.

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