DYNAMICS OF GALACTIC NUCLEI CONTAINING MASSIVE REMNANT STARS

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Abstract. We have examined the dynamical evolution of stellar system containing massive remnant stellar component. If individual mass of remnant stars is much heavier than that of normal stars which comprise most of the mass in the cluster, remnant stars quickly form a subsystem within the core of cluster of ordinary stars. The subsystem evolves on its own relaxation time scale which is very short. However, the post collapse expansion driven by the three-body binary heating becomes very slow because the expansion energy of the compact subcluster can be easily absorbed by surrounding cluster. The gravitational radiation can lead to the merger of binaries when binaries become very hard. A central seed black hole might form if repeated merger becomes very efficient. Otherwise, relatively stable two-component phase of central compact cluster of remnant stars surrounded by larger cluster of low mass stars would last for a long time.

1. Introduction

The stellar evolution inevitably produces remnant stars such as white dwarfs, neutron stars and black holes. In the old stellar systems dominated by low mass stars, these remnant stars can play important roles in dynamical evolution. For example, the concentrated dark mass indicated by spectroscopic observations in some nearby galaxies are interpreted as central black holes, but compact cluster of remnant stars can be an alternative explanation (Goodman & Lee 1989).

The dynamical evolution of spherical stellar systems have been studied in great detail using various numerical techniques. The core collapse is a natural consequence of the gravothermal instability existing in collisionless

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stellar systems. The time to reach the core collapse is a several multiple of initial half-mass relaxation time.

The relaxation time scale is difficult to define for galactic nuclei star cluster since there is no clear boundary. The central relaxation time scale can be a well define quantity, but most galactic nuclei are not resolved even with the HST (Lauer *et al.* 1995). Thus the physical conditions are very uncertain, but galactic nuclei are thought to have too long relaxation time to undergo core collapse within Hubble time.

However, the time scale for core collapse in units of relaxation time can become significantly shorter than single component case if more than one mass components are present (e.g. Inagaki 1985). In multi-mass clusters, the energy exchange between different mass groups leads to the segregation of mass. This process happens in a time scale shorter than core collapse time of a single component cluster. As a result of mass segregation, the central parts are dominated by heavier component. Since the velocity dispersion of the heaver component is smaller than the virial value, the central relaxation time scale becomes very short. Thus the core collapse of the heavy component becomes very fast. If the mass ratio between heavy and light components is very large, the whole process takes place in much shorter time scale than relaxation time scale of the cluster.

White dwarfs and neutron stars may be quite abundant but they can not accelerate the dynamical evolution significantly because the individual mass of these components is not much larger than the mass of normal stars. Black holes are not thought to be very abundant, but typical mass would be much larger than ordinary stars. Even a small fraction of mass in the form of black holes would be able to influence the dynamical evolution significantly. The mass of the black holes formed by stellar evolution is uncertain, but 10 $M_\odot$ appears to be a good representative value.

In the present paper, we discuss various aspects of dynamical evolution of dense stellar systems comparable to galactic nuclei containing small amount of massive remnant stars.

2. Dynamical Evolution of Two-Component Clusters

We restrict our discussion to the two-component star clusters for simplicity: one component representing old population of ordinary stars, and the other component representing remnant stars. The individual mass and abundance of remnant stars are taken as free parameters. Let's denote m_* and m_D as individual masses of normal and degenerate stars, respectively. The total mass stored in normal and degenerate stars are denoted by M_* and M_D, respectively. We assume that $m_D > m_*$ and $M_* \gg M_D$. Many of our discussions are only dependent on m_D/m_* and M_D/M_*, but we assume

TABLE 1. Minimum $t_c/t_{rh,0}$ for Two-Component Clusters

m_D/m_*	$(t_c/t_{rh,0})_m$	$(M_D/M_*)_m$
2.0	7.8	0.2
4.0	2.6	0.1
8.0	0.95	0.08
16.0	0.41	0.06

that $m_* = 0.7\ M_\odot$ when conversion to physical units is necessary.

The time for mass segregation is typically order of $t_r \times (m_*/m_D)$ where t_r is the relaxation time of the stellar system. However, the exact amount of time for mass segregation is difficult to define. But core collapse of the cluster of remnant stars gives well defined epoch and the core collape takes place in a very short time once the remnant stars are sufficiently segregated. Therefore, core collapse time can be a good measure for time scale for mass segregation. The collapse time is strongly dependent on the ratio of m_*/m_D, but it also varies with M_D/M_*. In Table 1, we have shown the minimum $t_c/t_{rh,0}$ for given m_D/m_*, where t_c is the collapse time and $t_{rh,0}$ is the initial half-mass relaxation time. In computing these numbers, we have used multi-mass Fokker-Planck equation and have assumed Plummer model as initial models. We have ignored any collisional effects in these calculations. Note that the collapse time of the single component cluster is $15.8t_{rh,0}$ (Cohn 1980). The last column of this table is the value of M_D/M_* giving minimum $t_c/t_{rh,0}$, but it is not an accurately determined number because the minimum is rather broad. From this table, it is clear that the dynamical evolution can be accelerated significantly by the presence of massive remnant stars.

The cluster of normal stars is essentially unaffected because the time scale for the dynamical evolution of the entire system is much longer than the collapse time. Thus the degenerate stars formed a subsystem within the core of ordinary star clusters. The half-mass radius of the degenerate component becomes smaller than the core radius of the normal component. Until the core collapse, the core radius of normal star component does not vary. Thus a compact cluster of degenerate stars can reside within the central core of much broader distribution of normal stars. If we determine the mass distribution based on the measured velocity distribution, there would be an indication of central point mass. As long as the half-mass radius of degenerate cluster remains to be much smaller than the resolution of the observations, it is impossible distinguish from a point mass.

Our assumption of neglecting the effects of collisions breaks down as the density of degenerate component cluster becomes very large. We now consider the collisional effects on the dynamics of the compact cluster.

3. Further Evolution of the Subsystem

Quinlan & Shapiro (1989; abbreviated as QS hereafter) studied the dynamical evolution of very dense stellar systems composed of neutron stars. As the density of the central degenerate component grows, the situation becomes similar to that considered by QS. The physical processes studied by QS include the formation of binaries via three-body and two-body processes. In addition, tidal interactions between degenerate and normal stars would take place in two-component clusters. We now examine these processes.

3.1. FORMATION AND EVOLUTION OF THREE-BODY BINARIES

The rate of formation of hard binaries can be expressed (Hut & Goodman 1993) as

$$\frac{dn_B}{dt} = 126 G^5 m^5 n^4 v^{-9}, \tag{1}$$

where n is the number density and v is the three-dimensional velocity dispersion. Compared to a single component case with ordinary stars only, the binary formation rate is greatly enhanced because the degenerate component has large n and m and small v. The binaries become energy source by releasing binding energy to the cluster through the interactions with surrounding stars. If the cluster is isolated so that there exists a finite escape velocity, the binaries are eventually ejected when they reach certain hardness, where the hardness is defined as

$$x \equiv \frac{3}{2}\frac{Gm}{av^2}. \tag{2}$$

Here a is the semi-major-axis of the binary orbit. The maximum hardness before the ejection depends on the central potential depth in single component case, but typically a few hundreds. However, the situation in two-component cluster is somewhat different in two aspects. First, the potential depth felt by degenerate component is much deeper because the velocity dispersion of the degenerate component is smaller. Thus the binaries can reach larger hardness than in the single component cluster. Second, the gravitational radiation energy loss could be important for binaries of compact stars if the orbital separation becomes smaller.

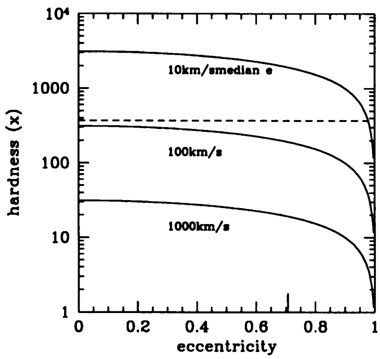

Figure 1. The border lines for gravitational radiation merger and ejection.

As binaries become tighter, typical recoil energy per collision increases but typical time interval between two successive collisions decreases while the time required for gravitational radiation to bring two object together decreases. A merger would take place before the binary is ejected if the gravitation radiation merger time scale becomes shorter than typical collision time scale.

The dynamical properties of a binary can be characterized by the hardness and the eccentricity (e) of the binary orbit. In Fig. 1, we have shown the the borderlines for a few processes in (e, x) plane. A typical binary is formed near $x = 3$ and wonders upward as a result of encounters with other objects. While the hardness changes mostly by strong encounters ($r_p \sim a$, where r_p is the pericentral distance of the binary-single relative orbit), eccentricities can be easily changed by week encounters. A thermal distribution of $f(e) \propto e$ can be established.

In computing the location of the border lines, we have assumed 10 $M_\odot$ black holes as degenerate stars (see Lee 1995 for details). The broken horizontal line near $x = 300$ is the typical hardness for binaries to escape as a result of single strong encounter. This is somewhat larger than typical value of $x \sim 100$ for a single component cluster because the potential depth measured by the velocity dispersion of degenerate stars becomes deeper.

The solid curves are the locations on which gravitational radiation merger time scale equals to the typical strong collision time. Therefore, binaries cannot cross this line: if the ejection line lies above this line, a binary would become mergers within the cluster. These lines are drawn for three different values of velocity dispersion because the physical orbital separation for a given hardness depends on the velocity dispersion. Thus the binaries in clusters with small velocity dispersion would be ejected (except for binaries with e close to 1). If there were some population of massive degenerate stars in globular clusters, they would have been ejected as suggested by Kulkarni, McMillan & Hut 1993.

Since the gravitational radiation merger time scale is very short for binaries with highly eccentric orbits, such binaries would be quickly depleted. Even in clusters with relatively small velocity dispersion, a significant fraction of binaries can become mergers. If the velocity dispersion is greater than 100 km/s, virtually all the binaries would become mergers. A typical binary can release energy of order of a few hundred kT until merger. Therefore the binaries of remnant stars formed by three-body processes are also an efficient heat source to the cluster. The core collapse can be stopped by the heating effects of binaries. Through the formation of binaries and subsequent merging, a population of more massive black holes grows. Eventually a single massive black can be formed by accreting many black holes if one waits for more than 'collision time' (Lee 1993).

If the velocity dispersion of the cluster were very large (say, 500 km/s or greater), the amount of heating per binary reduces significantly. The binaries may be unable to stop and reverse the core collapse. Thus one eventually reaches regime studied by QS who concluded that the formation of a single massive black hole is inevitable in the dense stellar systems composed of only neutron stars. By adopting more massive objects than neutron stars and two-component models, the growth to a single massive black hole would be even easier.

Although the degenerate binaries are efficient heat source for galactic nuclei with velocity dispersion of $\sim$ 100 km/s, there is a possibility that the efficiency could be significantly lower. The strong encounters between binaries and singles often involve complex motion among three objects. Any two of three objects can approach to very small distance, and the gravitational radiation energy loss can be very large. Merger can occur through this process for binaries with relatively large orbital separation. Some preliminary numerical calculations of binary-single scattering experiments are made and about 10 % of typical interactions for binaries with $e = 0.67$ (a median value for thermal distribution of eccentricity) and $x = 100$ at velocity dispersion of 100 km/s (Kong & Lee, this volume). More extensive computations are necessary in order to assess the importance of the gravitational radiation during the triple interactions.

3.2. CAPTURE BY GRAVITATIONAL RADIATION

If the energy loss by gravitational radiation exceeds the initial orbital kinetic energy, a binary can be formed. The rate of binary formation by this process is larger than that by three-body processes in low density phase.

However, binary formation is important only at high densities for both mechanisms. As the central density becomes very high, the three-body process dominates the two-body process unless the velocity dispersion is very large. For a typical condition during the post collapse expansion, the number of objects in the core becomes around 100. Then the velocity dispersion should be greater than 350 km/s in order for the two-body binary formation rate to exceed the three-body rate.

The gravitational radiation capture binaries have very large eccentricities and very small pericentral distances. Thus the gravitational radiation merger time scale is much shorter than any other time scales (QS; Lee 1994). Therefore they do not provide any energy to the cluster. It can only be considered as a process forming more massive black hole.

3.3. NORMAL-DEGENERATE TIDAL INTERACTIONS

Since the central parts of the entire cluster is dominated by degenerate component, close encounters between a degenerate and a normal star can occur. Close interactions between normal stars are much rarer. In stellar systems with relatively low velocity dispersion (order of 10 km/s) a tight binaries can be formed via tidal capture. If the velocity dispersion is large, the close encounters usually lead to the disruption of the normal component.

Some of the disrupted material will be unbound from the degenerate star just after the disruption because the stellar debris would have typical expansion velocity of order of several hundreds km/s. The maximum amount of escaping material will be 50% of the mass of the disrupted star. The remaining material will be orbiting around the degenerate star.

If the bound material is accreted onto the degenerate star, there will be strong radiation in the form of X-rays. The luminosity depends on the accretion rate which is quite uncertain. If the stellar debris forms a disk around the degenerate star, the disk mass is significant fraction of the central object. In such a massive disk, the viscous time scale is very short. The accretion rate can easily exceed the Eddington limit by a few orders of magnitude. Thus it is highly uncertain what the fate of the massive disk would be. It is possible that the majority of the material is blown out by strong radiation produced by the rapid accretion of matter. If this is the case, the entire energy released followed by a disruption of a normal star is be only a small fraction (i.e. $< 10^{-3}$) of the rest mass energy of the star. The entire duration of bright phase will be very short.

On the other hand, if the accretion rate is maintained at around the Eddington limit but there is no loss of disk mass, the entire duration to accrete the whole stellar debris will be relatively long. For example, 0.5 $M_\odot$ mass can be accreted in in approximately 2×10^6 years onto a 10 $M_\odot$

black hole if the accretion rate is limited by Eddington rate. The bolometric luminosity is 3.5×10^5 $L_\odot$ during this period. Thus the total luminosity in X-ray will be fairly large if there exist several systems having massive disks at a given time.

Because of these uncertainties, it is too early to dismiss the possibility of having a compact cluster of remnant stars in the central parts of galactic nuclei as a model for the dark central object on the basis of absence of strong X-ray emission. We now turn to numerical simulations of dynamical evolution of two-component clusters.

4. Fokker-Planck Models for the Dynamical Evolution

Here we present some of the model calculations based on the integration of multi-component Fokker-Planck equation. We assume spherical symmetry and isotropic velocity dispersion. The dynamical effect of binaries formed via three-body processes is included by adding a heating term to the Fokker-Planck equation. We also include the fact that the binaries formed via two body and three body processes eventually become mergers.

The heating of binaries enables the reversal of the collapse of the degenerate component. The density at the reversal is very large and there are only order of $10\sim$ 100 objects. Like the solutions for globular clusters, the central density exhibits rapid oscillation. However, as shown in Fig. 2 for the post collapse evolution of core radius of the degenerate component and half-mass radii of normal and degenerate components, the core of degenerate component does not expand in time scale of half-mass relaxation time of its own. The amplitude of core radius oscillation is very large, but the tendency for general expansion is not seen in this figure. In addition the half-mass radius of the degenerate component remains nearly constant, unlike the evolution of the single component case where $r_c \propto r_h \propto t^{3/2}$ after core collapse. This is due to the fact that the degenerate stellar system is embedded in the much larger stellar system of normal stars. The surrounding stellar system simply absorbs the expansion energy of the degenerate component. Since the energy content of the surrounding stellar system is very large, it can be considered as a heat reservoir.

If such a configuration of compact cluster of remnant stars surrounded by much larger cluster of normal stars is stable, concentration of dark mass in some of nearby galaxies can also be interpreted as the compact cluster of degenerate stars. There are two possibilities that this scenario cannot explain situations in our galaxy and nearby galaxies such as M31 and M32. First, the tidal interactions between a normal and a degenerate stars is estimated to be rather frequent. For a typical run with $M_{tot} = 10^7$ $M_\odot$, $M_D = 0.01 M_{tot}$, $m_D = 10$ $M_\odot$, we obtain roughly 10^{-3} encounters per year.

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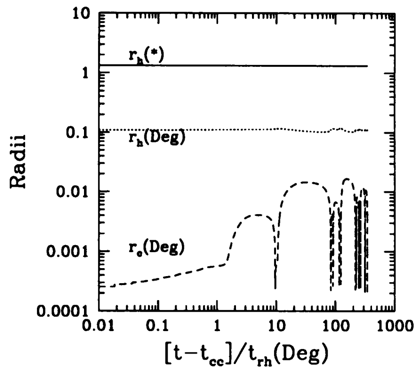

Figure 2. Core radius of normal component $[r_c(*)]$ and half-mass radii of normal $[r_h(*)]$ and degenerate $[r_h(Deg)]$ components.

Since the duration of active accretion phase can be up to 10^6 years after the disruption of a normal star if the accretion rate is regulated by Eddington limit (see §3.3), there will be order of 1000 X-ray emitting sources at any given time. This clearly exceeds the observational limit. On the other hand, if most of the massive disk is blown away by strong radiation produced by accretion of small mass, the X-ray luminosity could be lower by several orders of magnitudes.

Second, the merger of degenerate binaries via gravitational radiation could significantly alter the population of degenerate component. The formation rate is sufficiently small in low density phase of the oscillation so that it takes more than Hubble time to transform majority of degenerate stars into more massive population. However, the conditions in the core can become rather extreme during the high density phase of core oscillations. The entire mass of the core can be transformed into a single black hole. The changes in black hole mass in rapidly oscillating system has to be studied more carefully to decide the long term stability of highly segregated two component clusters.

5. Summary

The presence of massive degenerate component in a stellar system mainly composed of low mass stars can change the course of dynamical evolution significantly. The segregation of mass takes place in a short time scale. The central part of the stellar system is dominated by degenerate stars. The subsystem of degenerate component evolves on its own time scale while the surrounding system of normal stars remains nearly static because the relaxation time scale for this component is much longer than that of degenerate component.

As the core density of the degenerate system grows, various physical interactions occur. The binaries formed via three-body processes can release significant of energy to the cluster before they become mergers by gravitational radiation. If the potential depth of the stellar system is shallow (i.e., velocity dispersion is small) most of the binaries will be ejected. However, under the conditions of galactic nuclei where the escape velocity exceeds several hundreds km/s, binaries would become mergers well before they will reach the hardness for ejection.

The post collapse evolution driven by the binary heating is characterized by gravothermal oscillations, but the half-mass radius of the degenerate component stays nearly static because the expansion energy of the degenerate component is absorbed by much larger cluster of normal stars. The two-component phase may be dynamically unstable in the long run if the growth of the individual mass of degenerate stars grows rapidly. Typical time scale for the runaway growth of the mass is collision time, but it is difficult to define in a rapidly oscillating system.

The X-ray emission due to the accretion of debris of a tidally disrupted star onto the degenerate component can pose serious observational constraint on the presence compact cluster of remnant stars in quiet nuclei of galaxies. However, the physics after the disruption is sufficiently uncertain to draw any firm conclusion based on this argument.

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