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THE FORMATION AND MERGER OF COMPACT OBJECTS IN THE CENTRAL ENGINE OF ACTIVE GALACTIC NUCLEI AND QUASARS: GAMMA-RAY BURST AND GRAVITATIONAL RADIATION

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ABSTRACT

The production rate of compact objects, i.e., neutron stars (NSs) and black holes (BHs), in active galactic nuclei (AGNs) and quasars (QSOs), where frequent supernova explosions are used to explain the high metallicity, is very high because of the interaction between the accretion disk and main-sequence stars in the nucleus of the quasar. The compact object red giant (RG) star binaries can be easily formed because of the large captured cross section of the RG stars. The (NS/BH, NS/BH) binary can be formed after the supernova explosion of the (NS/BH, RG) binary. Intense transient gamma-ray emission (gamma-ray burst) and gravitational radiation can result from the merger of these two compact objects. Collision between the helium core (Hc) of the RG and the BH may also take place and may also result in long-duration gamma-ray bursts but no gravitational waves. We estimate that the merger rate of (NS/BH, NS/BH) binaries and (Hc, BH) is proportional to the metal abundance N V/C IV and can be as high as 10^{-3} [(N V/C IV)/0.01] yr^{-1} per AGN/QSO.

Subject headings: black hole physics — galaxies: active — galaxies: nuclei — gamma rays: bursts — gravitation — quasars: emission lines

1. INTRODUCTION

The basic physical scenario of active galactic nuclei (AGNs) and quasars is generally believed to be a supermassive black hole surrounded by an accretion disk which releases the observed huge body of energy (Rees 1984). However, in this model one prominent problem is the fuel. Syer, Clarke, & Rees (1991) investigate the possibility of an accretion disk capturing stars in the nucleus of a dense star cluster (within 1 pc) in order to remove the accretion fuel problem. This interesting interaction has been employed by Artymowicz, Lin, & Wampler (1993) and Zurek, Siemiginowska, & Colgate (1994) to explain the high-metallicity phenomena in active galactic nuclei and quasars, especially for broad absorption line quasars with extremely high metallicity (sometimes several hundred times that of the solar abundance; Shields 1996). It is interesting to note that this process also results in the formation and coalescence of compact objects in the central engine of active galactic nuclei and quasars which may be sources of frequent gamma-ray and gravitational-wave bursts.

Gravitational waves could soon be detected directly, even emitted from a source located at a cosmological distance, because several ground-based gravitational-wave experiments, including the Laser Interferometer Gravitational-wave Observatory (LIGO) (Abramovici et al. 1992), VIRGO, TAMA300, and GEO600 are under construction. The best-understood of all gravitational-wave sources are coalescing, compact binaries composed of neutron stars (NSs) and black holes (BHs). These NS/NS, NS/BH, and BH/BH binaries may give information about the equation of state of nuclear matter at high densities (Shibata, Nakamura, & Oohara 1992, 1993; Rasio & Shapiro 1994; Zhuge, Centrella, & McMillan 1994; Davies et al. 1994; Ruffert, Janka, & Schäfer 1996; Cheng & Dai 1998).

In addition, the observations of afterglows of gamma-ray bursts (GRBs) lend strong support to the cosmological origin of GRBs (Paczyński 1986; Mao & Paczyński 1992; Meegan et al. 1992; Piran 1992; see a concise review by Greiner 1998 for the afterglow and Piran 1998). Despite the effort of searching more than 20 yr for the counterparts of GRBs at other wave bands, no known population of objects in the universe has been identified with any GRB sources (e.g., Fenimore et al. 1993; Fishman & Meegan 1995; Band, Hartmann, & Schaefer 1998). There are two main reasons for this situation. First, the positional accuracy of a GRB detected by BATSE is so low that a large number of known objects is located in its error box. Second, the burst duration is so short that it is very difficult to use other means to reduce the error box. Although *BeppoSAX* has observed a dozen GRB afterglows, one of these sources can reduce its error box down to $\sim 1''$. But still no confirmed counterparts are identified, even for the well-observed GRB 970228 and GRB 970508. On the other hand, the observed isotropic and inhomogeneous distribution of GRBs detected by the BATSE instrument on board the *Compton Gamma-Ray Observatory* (*CGRO*) is best explained by a source population at cosmological distances.

Most cosmological GRB models involve compact objects. For example, (1) NS-NS/BH merger (e.g., Paczyński 1986; Eichler et al. 1989; Dermer 1992; Narayan, Piran, & Shemi 1991; Mao & Paczyński 1992); (2) collision between a BH and a helium core (Hc) or white dwarf (Fryer & Woosley 1998; Fryer et al. 1999); (3) the phase transition from an NS to a strange star (Cheng & Dai 1996); (4) the transition of normal nuclear matter to matter with pion condensation in an NS (e.g., Haensel et al. 1990; Muto et al. 1993); (5) a rapidly rotating NS with an extremely large magnetic field (Usov 1992; Duncan & Thompson 1992); (6)

a failed Type Ib supernova (Woosley 1993) or microquasar (Paczyński 1997), etc. Therefore, if we want to find the hosts of GRB sources, it is logical to look for cosmological sources with a lot of compact objects. From the stellar evolution point of view, the progenitors of compact objects, e.g., NSs, are massive stars (approximately 5–20 $M_\odot$). From the observations of afterglows of GRBs it has been deduced by Paczyński (1997) that GRBs may be associated with the star formation region. We note that most of the masses of the massive stars, consisting of a lot of heavy elements, will be ejected during the supernova explosion and a metal-rich region will be formed. Naturally, galaxies with a high abundance of compact objects should be metal rich. Therefore, it is logical to look for cosmological sources with high metal abundance. In order to observe the sources located at cosmological distance, these sources must be luminous. It should be noted that most AGNs/QSOs are metal rich (Artymowicz et al. 1993; Hamann et al. 1997). This may be the real reason why GRBs may be related to AGNs and QSOs as reported by Schartel, Andernach, & Greiner (1997) and Burenin et al. (1998), who claim that there is a possible association of GRBs with radio-quiet quasars and with AGNs, respectively. However, the physical scenario of this association remains unknown, if it is true that at least some of the GRBs are related to AGNs/QSOs. It has been suggested that GRBs may be produced in a star formation region which leads to the expectation that the burst rate of GRBs will be proportional to the formation rate of stars in the cosmological galaxies (Paczyński 1997). Because the lifetime of an AGN/QSO is rather short (generally less than 10^8 yr), the possible host objects of GRBs are mostly the ones related to galaxies. Alternatively, we suggest that the interaction between an accretion disk and stars in a dense cluster may lead to the formation of a large number of compact objects in the central engine of AGNs. The formation and interactions among the compact objects in the nuclei might be associated with GRBs. Therefore, AGNs are one kind of host object if GRBs are indeed associated with compact objects.

2. THE MODEL

The mechanism for the enhancement of metal-rich elements has been suggested as one possibility for the evolution of main-sequence stars, which are captured by the accretion disk surrounding the supermassive BH in the center of quasar (for a review see Lin & Papaloizou 1996). The captured stars would accrete material from the disk and increase their masses up to 50 solar masses in less than 10^4 yr. These massive stars evolve rapidly toward the supernova stage, and the ejecta of the supernovae provide enough heavy elements to produce the features suggested by observations. The metal abundance expressed in terms of the ratio between N V and C IV is related to the total number of captured main-sequence stars $N_{\rm MS}$ during the active phase of the quasar as follows (Artymowicz et al. 1993; Zurek et al. 1994):

$$\frac{\rm N\ V}{\rm C\ IV} \approx 0.01\left(\frac{N_{\rm MS}}{1.0 \times 10^5}\right) . \qquad (1)$$

However, this mechanism results in other implications, such as the formation of NSs/BHs in the vicinity of the accretion disk. As we will argue in § 2.1, there exists an efficient way to form compact object–compact object (i.e., NS/BH, NS/BH) binaries via the formation of compact object–red giant (RG) star (NS/BH, RG) binaries. The (NS/BH, NS/BH) binary will be formed after the explosion of the RG star. In such a scheme the merger rate of the (NS/BH, NS/BH) binary approximately equals the capture rate of the main-sequence star; therefore, it is proportional to the metal abundance. If the merger of the (NS/BH, NS/BH) binary or Hc of the RG and BH is one of the possible mechanisms of GRBs, then AGNs and quasars should associate with GRBs. In fact, the coalescence of two compact objects also produces intense transient gravitational waves which should be detected by LIGO/VIRGO in a 1 Gpc radius.

2.1. *Evolution of the Captured Stars in the Accretion Disk*

We assume that the nucleus of the quasar consists of a massive BH surrounded by an accretion disk, which is enclosed by a star cluster. The structure of the disk is described by the standard model in which the local height and the surface density of the accretion disk are given by (e.g., Frank, King, & Raine 1992)

$$\left(\frac{h}{R}\right) = 1.6 \times 10^{-3}\alpha^{-1/10}\dot{m}^{3/20}M_8^{-1/10}r_d^{1/8} , \qquad (2)$$

$$\Sigma = 1.7 \times 10^7\alpha^{-4/5}\dot{m}^{7/10}M_8^{1/5}r_d^{-3/4}\ ({\rm g\ cm^{-2}}) , \qquad (3)$$

respectively, and the inward drift velocity due to the outward transportation of the angular momentum in disk reads

$$v_r = 4.1 \times 10^4\alpha^{4/5}\dot{m}^{3/10}M_8^{-1/5}r_d^{-1/4}\ ({\rm cm\ s^{-1}}) , \qquad (4)$$

or the timescale of inward drift is

$$\tau_r = 4.0 \times 10^7\alpha^{-4/5}\dot{m}^{-3/10}M_8^{6/5}\left(\frac{r_d}{10^5}\right)^{5/4}\ ({\rm yr}) , \qquad (5)$$

where $\dot{m}$ is the dimensionless accretion rate scaled with the Eddington limit, α is the viscosity coefficient, $r_d = R/R_s$ is the radius of disk normalized by the Schwartzchild radius $R_s = GM_{\rm BH}/c^2$, and M_8 denotes the mass of the central BH ($M_{\rm BH}$) in units of $10^8\ M_\odot$.

The main-sequence stars in the star cluster will be captured by the disk, and the number of the captured main-sequence stars in the annular $R - R + dR$ is estimated as (Artymowicz et al. 1993)

$$dN = m_* G^2(\Sigma R dR)\,\frac{32\pi^{1/2}C_d v_0 \Delta T}{\sigma_0^3} ,$$
$$\approx 0.45\left(\frac{m_*}{M_\odot}\right)\left(\frac{v_0}{10^7\ {\rm pc^{-3}}}\right)\left(\frac{\Delta T}{10^8\ {\rm yr}}\right)\left(\frac{\sigma_0}{300\ {\rm km\ s^{-1}}}\right)^{-3}$$
$$\times\ \alpha^{-4/5}\dot{m}^{7/10}M_8^{11/5}r_d^{1/4}\,dr_d , \qquad (6)$$

where ΔT is the active period of quasar, v_0 is the number density of the star cluster at 1 pc in the range of about 10^7 pc^{-3} (Blandford 1991), σ_0 is the dispersion velocity of the star in the cluster, and $C_d \approx 6$. Integrating over the disk, there are $\sim 10^5$ main-sequence stars captured by disk in the active phase of the quasar or the captured rate is $\sim 10^{-3}$ yr^{-1}. The captured stars will corotate with the medium in the disk (Syer et al. 1991) and accrete gas from the disk with the Bondi rate until a gap appears in the disk with the condition that the star's Roche radius exceeds the disk scale height h (Lin & Papaloizou 1996). The timescale of Bondi accretion is

$$\tau_a = 1.40 \times 10^3 \alpha^{2/5} \dot{m}^{-1/10} M_8^{2/5} \left(\frac{r_d}{10^5}\right)^{3/4} \left(\frac{m}{M_\odot}\right)^{-1} (\mathrm{yr}) , \tag{7}$$

and the maximum accreted mass of the captured star is limited by

$$\left(\frac{m}{M_\odot}\right) = 17.7 \alpha^{-3/10} \dot{m}^{9/20} M_8^{7/10} \left(\frac{r_d}{10^5}\right)^{3/8} . \tag{8}$$

This condition also coincides with the fact that the Bondi radius ($r_\mathrm{B} = Gm_*/c_s^2$) does not exceed the local height h. With the typical parameters of the quasars and $\alpha = 1$, the maximum accreted mass of the captured stars is in the range of 10–20 $M_\odot$ (but the maximum mass of the captured stars could be much higher than 20 $M_\odot$ if α is much less than unity). The stars in this mass range will evolve off their main sequence quickly and likely become NSs plus a small fraction of BHs (see, e.g., Shapiro & Teukolsky 1983). For more massive stars ($m \geq 20\ M_\odot$) they could become NSs or BHs (Timmes, Woosley, & Weaver 1996). The simple formula of the evolution timescale for the main-sequence star is (Meurs & van den Heuvel 1989)

$$\tau_e = 10^{a_1} \left(\frac{m}{M_\odot}\right)^{a_2} , \tag{9}$$

where the indices a_1 and a_2 are tabulated in their Table 3. For the cases of interest we have $a_1 = 9.3$, $a_2 = -2$ for $3.8 \leq m/M_\odot \leq 12$ and $a_1 = 8.2$, $a_2 = -1$ for a star larger than 12 $M_\odot$. Substituting parameters for the lower mass case into equation (9), we obtain

$$\tau_e = 9.0 \times 10^6 \alpha^{3/10} \dot{m}^{-9/20} M_8^{-7/10} \left(\frac{r_d}{10^5}\right)^{-3/8} (\mathrm{yr}) . \tag{10}$$

The higher mass case will evolve faster than that given by equation (10). It has been estimated that the main-sequence stars start to be captured by the disk at the disk radius ~ 1 pc (Artymowicz et al. 1993), but the exact value of this radius is not crucial to our model. The more important radius R_c is that before which the captured stars finish the evolution of the supernova stage. This radius must be larger than that of the tidal radius $R_t = (M_\mathrm{BH}/m_*)^{1/3} r_*$, otherwise the captured stars will be disrupted by the central massive BH. This radius can be estimated by equating the radial inward drifting timescale equation (5), and the evolution timescale equation (11) and is given by

$$r_c = \frac{R_c}{R_s} = 4.0 \times 10^4 \alpha^{44/65} \dot{m}^{-6/65} M_8^{-76/65} . \tag{11}$$

It appears that this radius is always larger than that of R_t for typical quasar parameters.

2.2. *Formation of Binaries*

In the early stage, almost all of the captured stars can evolve into NSs/BHs with mass m_ns which will be ejected from the disk after supernova explosion. But these NSs/BHs can only shoot up to a scale height

$$h_\mathrm{ns} = \frac{v_\infty^2 R_c^2}{GM_\mathrm{BH}} , \tag{12}$$

where $v_\infty \sim 300$ km s^{-1} is the NS kick velocity produced by the supernova explosion. Taking the typical parameters, $h_\mathrm{ns} \sim 10^{16}$ cm, the compact stars will be oscillating up and down, crossing the disk. Artymowicz et al. (1993) also note the possibility of retrapping of the compact stars by the disk, but the following case is more interesting. Before evolving into a compact star, the captured star will go through the RG phase with radius R_RG and mass M_RG. During the close encounter with an NS, the RG star would undergo substantial tidal deformation at the cost of a part of the relative kinetic energy of the orbit. Such a tidal process can eventually dissipate the total positive energy of the initial unbound orbit via oscillations and heating, and an (NS/BH, RG) binary system will be created. One might argue that the velocity dispersion of the NS/BH is much larger than the escape velocity of the RG at its surface (about 70 km s^{-1}). However, it is interesting to note the following situation. The surface density of the RG, $\Sigma_\mathrm{RG} \sim M_\mathrm{RG}/R_\mathrm{RG}^2 \sim 10^7$ g cm^{-2}, is much larger than that of the disk, $\sim 10^3$ g cm^{-2}, at 0.1 pc. This leads to an efficient dissipation of the NS/BH kinetic energy in the process of encountering the RG's envelope. The probability of the NS/BH encountering the dense envelope of the RG can be easily estimated:

$$f = \frac{S_\mathrm{RG}}{S_\mathrm{disk}} \sim 10^{-2} , \tag{13}$$

where S_RG is the total surface area of all RGs and S_disk is the area of the disk capturing the main-sequence star. The drag force acting on the NS/BH by the dense envelope of the RG reads (Artymowicz et al. 1993)

$$F_d = \frac{4\pi G^2 m_\mathrm{ns}^2 \rho C_d}{v_\infty^2} . \tag{14}$$

After N times of encountering the disk, the kinetic energy of the NS/BH will be reduced significantly so that the NS/BH can be captured by the RG through tidal process,

$$N = \frac{v_\infty^4}{8\pi f G^2 m_\mathrm{ns} C_d \Sigma_\mathrm{RG}} , \quad \sim 10^4 \left(\frac{f}{0.01}\right)^{-1} \left(\frac{\Sigma_\mathrm{RG}}{10^7\ \mathrm{g\ cm^{-2}}}\right)^{-1} \left(\frac{v_\infty}{300\ \mathrm{km\ s^{-2}}}\right)^4 , \tag{15}$$

and the capture timescale of the NS/BH by the RG envelope is about

$$\tau_\mathrm{ns,RG} = N \frac{h_\mathrm{ns}}{v_\infty} \sim 10^5\ \mathrm{yr} , \tag{16}$$

which is slightly shorter than the lifetime of the RG; therefore, a large fraction of the RG can be captured by the compact objects in the vicinity of the disk to form (NS/BH, RG) binaries if we take into account the interaction between the NS/BH and the envelope of RG. Let us consider the tidal capture rate in more detail. The distance D for the tidal capture to form an (NS/BH, RG) binary can be estimated as (Bhattacharya & van den Heuvel 1991)

$$D \approx 1.75 R_\mathrm{RG} \left(\frac{m_\mathrm{ns}}{M_\mathrm{RG}} \frac{m_\mathrm{ns} + M_\mathrm{RG}}{M_\odot} \frac{R_\odot}{R_\mathrm{RG}}\right)^{1/6} \left(\frac{50\ \mathrm{km\ s^{-1}}}{v_\mathrm{ns}}\right)^{1/3} , \tag{17}$$

where v_{ns} is the reduced velocity of the compact star. The cross section of this capture process is given by

$$\sigma \approx \pi D^2 \left[1 + \frac{2G(m_{ns} + M_{RG})}{v_{ns}^2} \right] , \quad (18)$$

and is $\sim 3 \times 10^{28}$ cm^2 for typical parameters. The formation rate of the (NS/BH, RG) binary can thus be written as

$$\frac{dN_{NR}}{dt} = \left(\frac{N_{ns}}{V_{ns}}\right)\left(\frac{N_{RG}}{V_{RG}}\right) v_{ns} \sigma V_{RG} = k N_{ns} N_{RG} , \quad (19)$$

where N_{ns} and $V_{ns} \sim h_{ns} R_c^2$ (N_{RG} and V_{RG}) are the number and occupied volume of compact stars (RG stars), respectively and constant $k = v_{ns} \sigma / V_{ns}$. It should be noted that N_{ns} and N_{RG} are time dependent because the presence of the (NS/BH, RG) binary formation results from the tidal interaction between compact stars and RG stars. The time-dependent numbers of compact stars and RG stars obey the following equations:

$$\frac{dN_{RG}}{dt} = \Gamma - k N_{ns} N_{RG} , \quad (20)$$

$$\frac{dN_{ns}}{dt} = \frac{N_{RG}}{\tau_{RG}} - k N_{ns} N_{RG} , \quad (21)$$

where Γ is the capture rate of main-sequence stars by the disk and τ_{RG} represents the evolution timescale from RG star to NS/BH (about a few times 10^5 yr). These nonlinear equations can be analytically resolved into some interesting stages.

1. When $t \leq 1/\Gamma$, the production of RG stars dominates, and we have

$$N_{RG} \approx \Gamma t, \text{ and } N_{ns} \approx \left(\frac{\Gamma}{\tau_{RG}}\right) t^2 . \quad (22)$$

2. In steady state, the numbers of compact stars and RG stars reach constants, i.e.,

$$N_{RG}(\infty) = \tau_{RG} \Gamma, \text{ and } N_{ns}(\infty) = \frac{1}{k \tau_{RG}} . \quad (23)$$

It is clear that the (NS, RG) binary formation rate is a constant, i.e., $dN_{NR}/dt = \Gamma$.

2.3. *Coalescence of the (NS/BH, NS/BH) and (BH, Hc) Binaries*

The evolution of massive binaries leads to two possibilities: (1) Merging of the Hc of the RG and BH or (2) (NS/BH, NS/BH) binary formations and merging. The first case occurs for very close binaries in which the BH companion encounters the Hc before the secondary evolves into a compact object. This process was recently suggested as a GRB mechanism by Fryer & Woosley (1998). The second corresponds to the case in which the secondary evolves into a compact star faster than that from the spiral-in process. Then the (NS/BH, NS/BH) binaries are formed and eventually merge to emit intense transient gamma rays and gravitational waves. The estimations of the above processes are given below.

The captured compact star may spiral-in the RG star with a core mass M_{core} and envelope mass M_{en}. Many detailed calculations have been done (e.g., Bodenheimer & Taam 1984; Taam & Bodenheimer 1989; Taam et al. 1997). A rough estimation of the final separation of the binary after spiral-in can be made by comparing the binding energy of the envelope with the difference in total energy of the binary before and after spiral-in (Webbink, Rappaport, & Savonije 1983; Verbunt 1993):

$$\frac{D_f}{D_i} = \frac{M_{core}}{M_{RG}} \left(1 + \frac{2D_i}{\alpha_* \lambda R_L} \frac{M_{en}}{m_{ns}}\right)^{-1} , \quad (24)$$

where D_i and D_f are the initial and final separation, respectively, R_L is the Roche radius, which is given by (Eggleton 1983)

$$\frac{R_L}{D_i} = \frac{0.49}{0.6 + q^{-2/3} \ln(1 + q^{1/3})} , \quad (25)$$

where q is the mass ratio of the (NS/BH, RG) binary system, and α_* is the efficiency with which released binary energy is used to lift the envelope; λ is a factor depending on the mass distribution in the envelope of the RG. Their product is often taken to be 0.20. The core mass of the RG star for $M_{RG} \geq 7\, M_\odot$ is given by (Iben 1993)

$$\frac{M_{core}}{M_\odot} = 0.058 \left(\frac{M_{RG}}{M_\odot}\right)^{1.57} . \quad (26)$$

The radius of core is given by (Paczyński & Kozlowski 1972; Pols & Marinus 1994; R. Wijers 1998, private communication)

$$\frac{R_{core}}{R_\odot} = 0.22 \left(\frac{M_{core}}{M_\odot}\right)^{0.6} . \quad (27)$$

If D_f is smaller than the sum $R_{core} + R_{ns} \approx R_{core}$, after spiral-in the compact star merges with the core of the RG star. We have calculated some typical cases listed in Table 1. It can be found that an RG more massive than 18 $M_\odot$ will merge with the Hc before they form an (NS/BH, NS/BH) binary. Even if the companion star is an NS, it may efficiently accrete material from the RG to become a BH during the spiral-in process (Chevalier 1996; Fryer & Woosley 1998). Therefore, the merger of the (NS/BH, Hc) binary can become a GRB as described by Fryer & Woosley (1998).

There are two possible ways to destroy the formed (NS/RG, RG) binaries: (1) by combining the gravitation of the central BH and the dense star cluster or (2) by the third encounter from the cluster. It has been shown by Saslaw (1985) that the chance of the second way is rather small. We can now estimate the action of the first way. If the tidal force from the gravitation of a central massive BH and dense star cluster exceeds the interacting force between the two components, then the (NS/BH, RG) will be disrupted by the tidal force. The tidal force reads

$$F_{tid} = \frac{G(M_{BH} + M_{SC})(m_c + M_{RG})}{R^2} \frac{D_i}{R} , \quad (28)$$

where M_{SC} is the mass of dense star cluster and m_c is the mass of the compact object. Then the ratio between the tidal

TABLE 1

THE CALCULATION OF BINARY FORMATIONS

M_{RG}	M_c	R_c	D_i	D_f	e	D_{ns}	t_m (yr)	Type
10.0......	2.155	0.349	296.021	0.621	0.270	0.788	0.804×10^7	(NS, NS/BH)
11.0......	2.503	0.381	295.468	0.613	0.394	0.855	0.796×10^7	(NS, NS/BH)
12.0......	2.869	0.414	295.003	0.607	0.525	0.925	0.635×10^7	(NS, NS/BH)
13.0......	3.253	0.446	294.606	0.601	0.662	0.999	0.359×10^7	(NS, NS/BH)
14.0......	3.655	0.479	294.264	0.596	0.805	1.077	0.987×10^6	(NS, NS/BH)
15.0......	4.073	0.511	293.966	0.592	0.955	1.158	0.131×10^5	(NS, NS/BH)
16.0......	4.507	0.543	293.704	0.589	>1	...	...	...
17.0......	4.957	0.575	293.472	0.586	>1	...	...	...
18.0......	5.423	0.607	293.265	$0.584 < R_c$	...	...	...	(Hc, BH)
19.0......	5.903	0.638	293.079	$0.582 < R_c$	...	...	...	(Hc, BH)
20.0......	6.398	0.670	292.911	$0.580 < R_c$	...	...	...	(Hc, BH)

NOTE.—All parameters are in solar units except e and t_m(yr). The mass of the compact star is taken to be 1.4 $M_\odot$.

force and the gravitational force (F_B) between the two components is

$$\frac{F_{tid}}{F_B} = \frac{M_{BH} + M_{SC}}{M_{RG}} \frac{M_{RG} + m_c}{m_c} \left(\frac{D_i}{R}\right)^3 \approx 10^{-4} , \quad (29)$$

which means that the formed binary can survive in its surroundings. On the other hand, the spiral-in process consequently takes place in the binary very fast. The timescale of this process can be roughly estimated under the assumption that the formed (NS/BH, RG) binary keeps the total angular momentum constant. According to Verbunt (1993), this timescale reads

$$\tau_{sp} = \frac{1}{2(1 - m_c/M_{RG})} \frac{M_{RG}}{\dot{M}} \approx \frac{1}{2} \frac{M_{RG}}{\dot{M}} , \quad (30)$$

where $\dot{M}$ is the rate of mass transfer onto the compact object. For the case of the RG as a donor in the (NS/BH, RG) binary system, $\dot{M}$ can be estimated from Bhattacharya & van den Heuvel (1991),

$$\dot{M} = 1.4 \times 10^{-2} M_1^{2.25} R_1^{0.75} \; (M_\odot \; yr^{-1}) , \quad (31)$$

where $M_1 = M_{RG}/M_\odot$ and $R_1 = R_{RG}/R_\odot$. We thus obtain

$$\tau_{sp} \approx 35.7 M_1^{-1.25} R_1^{-0.75} \; (yr) . \quad (32)$$

From the above two equations we have the typical timescale for the case of an RG with mass 10 $M_\odot$, $\tau_{sp} \sim 2$ yr. This simply means that the newly formed (NS/BH, RG) binary will reach the final stable configuration D_f (listed in Table 1) within 2 yr and become hard from the soft state very rapidly. It is thus viable to form a hard binary in the accretion disk. Furthermore, it has been shown in more detail by Magorrian & Tremaine (1999) that the highest tidal disruption rate 10^{-4} yr^{-1} only takes place in faint galaxies ($L < 10^{10} L_\odot$). The tidal disruption of a giant star could produce a flare as often as every 10^5 yr. Therefore, it is robust to believe that the present model of star-disk interaction dominates over tidal capture by supermassive BHs located at the center of the AGN/QSO in the active phase of the AGN/QSO.

The detailed study of orbital changes due to the explosion of supernovae can be found in Pols & Marinus (1994) and Portegies Zwart & Verbunt (1996). On the other hand, Verbunt (1993) argued that this effect can be estimated by assuming that the explosion is instantaneous and the positions and velocities of the stars are the same after the explosion as before the explosion (Dewey & Cordes 1987). This implies that the distance D_f between the compact star and the core star before the explosion is the periastron distance after the explosion and that the periastron velocity of the new orbit is the same as the orbital velocity in the presupernova orbit. Therefore, the eccentricity is given by (Verbunt 1993)

$$e_{ns} = \frac{M_{core} - m_{ns}}{2m_{ns}} . \quad (33)$$

The mass center of the binary has obtained a speed v_{cm} because of the mass loss and is given by

$$v_{cm} = e_{ns} v_1 , \quad (34)$$

where $v_1 = (GM_{core}/D_f)^{1/2} \sim 10^8 (M_{core}/4 \; M_\odot)^{1/2} (D_f/1 \; R_\odot)^{1/2}$ cm s^{-1} is the orbital velocity of the exploding component before explosion. This velocity will make the (NS/BH, NS/BH) binary shoot up to a scale height of $\sim 10 h_{ns}$. Furthermore, the orbit of the binary is sufficiently small that it should be circularized by tidal interaction, and the radius D_{ns} of the circular orbit is given by

$$D_{ns} = (1 + e_{ns}) D_f . \quad (35)$$

In Table 1 we list some possible values of e_{ns} and D_{ns} by assuming $m_{ns} = 1.4 \; M_\odot$. We can see that e is larger than unity when M_{RG} is larger than 15 $M_\odot$. This means that after explosion the binary will be broken. For $m_{ns} = 3 \; M_\odot$, we find that e is always less than unity and D_f is larger than R_c even when M_{RG} equals 20 $M_\odot$, in other words, there is no merger of the massive BH and Hc.

There are two interesting consequences of the newborn (NS/BH, NS/BH) binary. First, the kick velocity will carry the binary to leave the disk up to a distance of about $10 h_{ns} \sim 10^{17}$ cm. Second, since the separation of the two compact stars in the (NS/BH, NS/BH) binary is $\sim D_{ns}$, the gravitational radiation of the binary will make these two compact stars merge on the timescale of (Peter 1964)

$$t_m(D_{ns}, e) = \frac{12}{19} \left(\frac{D_{ns}^4}{\beta c_1^4}\right) \mathrm{Int}(e) , \quad (36)$$

with

$$c_1 = \frac{e^{12/19}}{(1-e^2)}\left(1+\frac{121}{304}e^2\right)^{820/2299}, \quad (37)$$

$$\beta = \frac{64}{5}\frac{G^3 M_1 M_2 (M_1+M_2)}{c^5}, \quad (38)$$

and Int(e) is the integral (see eq. [5.14] in Peter 1964). Therefore, the compact star merger rate should be about Γ. One should not be surprised by the short timescale of the merger since t_m is proportional to $D_{\rm ns}^4$ while most of $D_{\rm ns}$ is less than 1 $R_\odot$, and $t_m \propto (1-e^2)^{7/2}$ for larger eccentricity.

3. DISCUSSION

In this paper we suggest that the metallicity of metal-rich quasars results from the capture of the main-sequence stars by the accretion disk surrounding the central massive BH of quasars and that the captured stars can increase their masses by accretion so they can evolve off their main-sequence branch and move toward the supernova stage, which provides the observed metal abundance. Then the remnant stars are likely compact stars, i.e., NSs or BHs. We have shown that the NS/BH density in the vicinity of the disk will be high enough for a population of (NS/BH, RG) binaries which can eventually evolve to become either (1) (NS/BH, NS) binaries if the mass of the RG is less than 15 $M_\odot$ and merge on a timescale of a few million years or (2) a (NS/BH, Hc) binary.

In a wide range of cosmological GRB models the compact star merger plays an essential role. The main-sequence star capture rate $\Gamma = 10^{-3}$ yr^{-1}[(N v/C iv)/0.01] is proportional to the metal abundance N v/C iv and the compact object binary formation rate equals the main-sequence star capture rate in our simple model. Therefore, the GRB burst rate $R_{\rm GRB}$ in AGNs or QSOs can be estimated as

$$R_{\rm GRB} \sim 10^{-3}\eta\,\frac{\text{N v/C iv}}{0.01}\ \text{yr}^{-1}\ \text{QSO}^{-1}, \quad (39)$$

where η is the beaming factor of the gamma rays, which reduces the observed probability of GRBs resulting from the compact star mergers (e.g., η is 0.1–0.01 for an NS/NS merger; Ruffert, Janka, & Schafer 1996; Ruffert et al. 1997; Ruffert & Janka 1998). Such an estimated GRB rate in metal-rich quasars is much higher than that of ordinary galaxies, e.g., the merger rate due to the mass exchange and gravitational radiation losses gives a conservative rate $\sim 10^{-6}$ yr^{-1} (Phinney 1991; Narayan et al. 1992) or a higher rate 10^{-4} to 10^{-5} yr^{-1} (Tutukov & Yungelson 1993; Portegies Zwart & Verbunt 1996) in light of the calculations of binary evolution. Of course, the population of AGNs/QSOs is only 1% of normal galaxies, which makes the total burst rate for these two classes of objects comparable. However, the burst rate for individual AGNs/QSOs, which has an exceptionally high metal abundance, could be very large. There is a much higher possibility that the not yet identified host of a GRB may be an AGN/QSO with very high metallicity.

Recently, Dokuchaev, Eroshenko, & Ozernoy (1998) proposed the possibility that GRBs originate from the evolved galactic nuclei. In their model GRBs result from the coalescence of the compact object binaries which are formed because of the dynamical evolution of the cluster and the dissipation of gravitational radiation. Carter (1992) proposed that GRBs are produced by the tidal disruption by the central supermassive BH. Rees (1988) even pointed out that the rate of tidal disruption could be 10^{-4} yr^{-1}, which is significantly lower than the capture rate (see eq. [6]) and the formation rate of (NS/BH, NS/BH) binaries; particularly, the whole star (unless it is a giant star) will be swallowed by the supermassive BH with mass greater than $10^8\ M_\odot$ since the Roche radius R_t will lie within the horizon radius of the BH. Therefore, it is believed to be an AGN/QSO GRB rate because the presently proposed process may dominate the tidal capture of star by the central BH. One might argue that there is no AGN/QSO at the locations of GRB 970228 and GRB 970508 which are detected by *BeppoSAX*, therefore it is unlikely that GRBs are related to this class of object. However, in order to locate the accurate position the *BeppoSAX* is restricted to long-duration GRBs. Popham, Woosley, & Fryer (1998) show that only (BH, Hc) merger can produce a long-duration burst; other mergers (e.g., [NS/BH, NS/BH]) will not produce a long-duration burst. It is important to note that the lifetime of an AGN is typically 10^8 yr; alternatively, the present paper proposed that at least some GRBs may originate from the active nuclei because of the interaction between the star in the cluster and accretion disk, roughly 1% of the observed GRBs. In our model only very low mass compact stars and high-mass RG binaries can form (BH, Hc) mergers. For a power-law mass function, such binaries will be a very small fraction. It is not too surprising to not identify any AGNs/QSOs with GRB 970228 and GRB 970508 which are long-duration bursts. Interestingly, there are two GRBs with small error boxes, in which AGNs were found. It was reported by Drinkwater et al. (1997) that the possible X-ray counterpart of GRB 920501 is related to a Seyfert 1 galaxy at $z = 0.315$. Piro et al. (1998) report that the first X-ray location of a GRB by *BeppoSAX* (within a 3′ radius) contains the quasar 4C 49 with $z = 1.038$. Finally, we want to point out that the basic energy mechanism of GRBs in our model is the same as those proposed by other authors, namely, GRBs result from the mergers of compact binaries and our model mainly concerns the formation rate of the binaries and the location of GRBs. Since our model burst rate is proportional to the metal abundance (cf. eq. [39]), we shall predict that if the GRBs can be identified with AGNs/QSOs, these AGNs/QSOs must have high metal abundance.

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