

Formation of Intermediate-Mass Black Holes in Circumnuclear Regions of Galaxies

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Abstract

Recent high-resolution X-ray imaging studies have discovered possible candidates of intermediate-mass black holes with masses of $M_{\bullet} \sim 10^{2-4} M_{\odot}$ in circumnuclear regions of many (disk) galaxies. It is known that a large number of massive stars are formed in a circumnuclear giant H II region. Therefore, we propose that continual merger of compact remnants left from these massive stars is responsible for the formation of such an intermediate-mass black hole within a timescale of $\sim 10^9$ years. A necessary condition is that several hundreds of massive stars are formed in a compact region with a radius of a few pc.

Key words: black holes — galaxies: starburst — galaxies: star clusters — X-rays: sources

1. Introduction

Recent sensitive, high-resolution X-ray imaging studies have found unusually bright, compact X-ray sources in circumnuclear regions of many (disk) galaxies [Colbert & Mushotzky 1999 (hereafter CM99), Okada et al. 1998; Ptak & Griffiths 1999; Matsumoto & Tsuru 1999; Makishima et al. 2000]. Prior to these observations, it has been known that some nearby galaxies have luminous X-ray sources in their circumnuclear regions (Fabbiano & Trinchieri 1987; Kohmura et al. 1994; Petre et al. 1994; Takano et al. 1994; Colbert et al. 1995; Reynolds et al. 1997; see for a review Fabbiano 1988). The observational properties of such circumnuclear X-ray sources are summarized as follows (e.g., CM 99); 1) ROSAT X-ray luminosities, $L_X(0.2\text{--}2.4 \text{ keV}) \sim 10^{37} - 10^{40} \text{ ergs s}^{-1}$ with a mean of $3 \times 10^{39} \text{ ergs s}^{-1}$; note that some of them are also detected in the hard X ray and thus the total X-ray luminosities are higher by about one order of magnitude than the above values, 2) the mean displacement between the location of the compact X-ray source and the optical photometric center of the galaxy is $\sim 390 \text{ pc}$, and 3) they are common; the detection rate of such compact X-ray sources is $\gtrsim 50\%$.

Possible origins of these sources are; 1) black hole X-ray binaries, 2) low-luminosity AGN, 3) young X-ray luminous supernovae, or 4) a new X-ray population (e.g., CM99). Since the Eddington luminosity of a $1.4 M_\odot$ accreting neutron star is $10^{38.3} \text{ ergs s}^{-1}$, the luminous compact X-ray sources cannot be explained by a single accreting neutron star. If they are black hole X-ray binaries, their masses are estimated to be $M_\bullet \sim 10^2 - 10^4 M_\odot$; i.e., intermediate-mass black holes (hereafter IMBHs). This urges us to consider how such IMBHs can be formed in circumnuclear regions of galaxies.

One of ideas may be that they are formed through the collapse of massive clouds (see Rees 1978). In typical disk galaxies, gas clouds are present as a form of giant molecular gas clouds; hereafter GMCs. A typical GMC has the following characteristics (e.g., Blitz 1993); 1) the mass, $M_{\text{GMC}} \simeq (1 - 2) \times 10^5 M_\odot$, 2) the mean diameter, $D_{\text{GMC}} \simeq 45 \text{ pc}$, 3) the volume, $V_{\text{GMC}} \simeq 9.6 \times 10^4 \text{ pc}^3$, 4) the average density of H_2 , $\bar{n}_{\text{H}_2} \simeq 50 \text{ cm}^{-3}$, and 5) the mean column density of H_2 , $\bar{N}_{\text{H}_2} \simeq (3 - 6) \times 10^{21} \text{ cm}^{-2}$. Although the typical kinetic temperature is $T_{\text{kin}} \sim 10 \text{ K}$, the sound speed, c_s , is generally higher than the velocity dispersion derived from the kinetic temperature because the turbulence plays an important role in GMCs; therefore, $c_s \sim 1 \text{ km s}^{-1}$. If a GMC is perturbed gravitationally by some physical mechanism, it is likely that it begins to experience fragmentation, resulting in the formation of sub-giant molecular clouds. Such fragmentation could occur preferentially in denser parts of the GMC. Since a

typical H_2 density and a typical kinetic temperature in such dense parts are $n_{\text{H}_2} \sim 10^4 \text{ cm}^{-3}$ and $T_{\text{kin}} \sim 10 \text{ K}$, respectively, we obtain a Jeans' mass of $m_{\text{J}} \sim \lambda_{\text{J}}^3 \rho_{\text{H}_2} \sim 20 M_{\odot}$ for $\lambda_{\text{J}} = c_{\text{s}}(\pi/G\rho_{\text{H}_2})^{1/2} \sim 0.36 (c_{\text{s}}/0.3 \text{ km s}^{-1}) \text{ pc}$ and $\rho_{\text{H}_2} = n_{\text{H}_2} m_{\text{H}_2}$ where m_{H_2} is the mass of a hydrogen molecule (Jeans 1929). Therefore, IMBHs may not be formed directly from such massive gas clouds.

Instead, in this Letter, we propose that an IMBH is formed by continual merging of compact remnants (i.e., neutron stars and black holes) left from massive stars in a giant H II region. The reason for this is that giant H II regions are often observed in circumnuclear regions of disk galaxies (e.g., Kennicutt, Keel, & Blaha 1989 and references therein; see for the formation mechanism of such circumnuclear giant H II regions, Elmegreen 1994). We also discuss some other proposed mechanisms responsible for the formation of IMBHs.

2. Proposed Model

2.1. Dynamical Relaxation of Massive-Star Compact Remnants

It has been considered that one plausible mechanism for the formation of supermassive black holes (SMBHs) in galactic nuclei is to pile up compact remnants of massive stars born in nuclear regions (e.g., Spitzer & Saslaw 1966; Spitzer & Stone 1967, Spitzer 1969; Saslaw 1973; Begelman & Rees 1978; Weedman 1983; Norman & Scoville 1988; Quinlan & Shapiro 1989, 1990; Lee 1995; Taniguchi, Ikeuchi, & Shioya 1999). On the analogy of this mechanism, we investigate the dynamical evolution of compact remnants left from massive stars born in the core of a giant H II region in circumnuclear regions of galaxies.

Typical masses of IMBHs lie in the range between $\sim 10^2 M_{\odot}$ and $\sim 10^4 M_{\odot}$ (CM99). Therefore, we investigate a possibility that an IMBH with mass of $10^3 M_{\odot}$ can be formed from mergers of compact remnants left in the core of a giant H II region. We consider a case that N massive stars with masses higher than $8 M_{\odot}$ are formed within a sphere with a radius of r_{cl} . Here it is noted that all such massive stars yield a compact remnant after the supernova explosion while the core of stars with masses less massive than $8 M_{\odot}$ evolves into a white dwarf. It is known that the mass of a neutron star is $\approx 1.4 M_{\odot}$ while that of a stellar-size black hole is from a few M_{\odot} to $\approx 10 M_{\odot}$; e.g., Brown & Bethe (1994) suggested that main-sequence stars with $18 M_{\odot} < m_* < 25 M_{\odot}$ evolve to low-mass black holes ($m_{\bullet} \simeq 1.5 M_{\odot}$) while stars with $m_* > 25 M_{\odot}$ evolve to high-mass black holes ($m_{\bullet} \gtrsim 10 M_{\odot}$). However, the mass function for giant H II regions has not yet been well known. Therefore, in the above estimate, we have assumed for

simplicity that all the compact remnants are black holes with a mass of $2 M_{\odot}$ and thus 500 seed compact remnants are necessary to make an IMBH with a mass of $10^3 M_{\odot}$.

All the massive stars die within a timescale of $\sim 10^7$ years and then a cluster of compact remnants will result in. The candidates of IMBHs are observed in circumnuclear regions of galaxies (i.e., a typical radial distance is $R \simeq$ a few 100 pc). At such a distance, the rotation curve of galaxies may be described by the rigid rotation (e.g., Rubin et al. 1985; cf. Sofue 1997); we assume that the rigid rotation continues up to a radius of $R = 1$ kpc and reaches the maximum rotation velocity of $v_{\text{rot}} = 200 \text{ km s}^{-1}$. If a giant H II region is formed at $R = 100$ pc, the cluster of massive stars (and thus the cluster of compact remnants too) is influenced by the mass contained within $R = 100$ pc. This mass is estimated to be $M \sim Rv_{\text{rot}}^2/G \sim 9 \times 10^6 R_{100}^3 M_{\odot}$ where R_{100} is the radial distance in units of 100 pc; note that $v_{\text{rot}} = 20R_{100} \text{ km s}^{-1}$. The radius of the remnant cluster can be estimated as the tidal radius,

$$r_{\text{cl}} \sim r_{\text{tidal}} \sim R[Nm_{\bullet}/(2M)]^{1/3} \sim 3.8N_{500}^{1/3}m_{\bullet,2}^{1/3} \text{ pc} \quad (1)$$

where N_{500} is the number of compact remnants in units of 500 and $m_{\bullet,2}$ is the mass of a compact remnant in units of $2 M_{\odot}$. In this case, the cluster can be relaxed dynamically with a timescale of

$$\tau_{\text{dyn}} \sim N^{1/2}G^{-1/2}r_{\text{cl}}^{3/2}m_{\bullet}^{-1/2} \sim 1.8 \times 10^9 \text{ y}. \quad (2)$$

Since this timescale is shorter than the age of galaxies, this mechanism may be responsible for the formation of IMBHs in circumnuclear regions of galaxies.

It is noted that the dynamical situation for a cluster of compact remnants considered here is completely different from both that for a cluster of compact remnants in globular clusters (e.g., Kulkarni, Hut, & McMillan 1993) and that for a cluster of compact remnants in the nuclear region of galaxies (e.g., Weedman 1983; Lee 1995 and references therein) because low-mass stars dominate the cluster gravitational potential for the latter two cases. On the other hand, it is expected that massive stars may be preferentially formed in the core. Since supernovae could blow the gas resided originally in the core region, compact remnants themselves may dominate the cluster gravitational potential. Furthermore, lifetimes of OB stars are less than $\sim 10^7$ years, being much shorter than the dynamical relaxation timescale estimated above. Therefore, the star cluster evolves to a cluster of compact remnants quickly. Some black holes may be ejected from the cluster by the dynamical effect during the formation of black hole binaries through the three-body encounters (Spitzer 1987; Kulkarni et al. 1993). However, this effect is negligible if $N \gtrsim 100$ (e.g., Binney & Tremaine 1987); this is indeed the case discussed here.

Then we investigate what kind of massive star formation is necessary. We estimate an average number density of gas, $n_{\text{H}} = M_{\text{gas}}/[(4\pi/3)r_{\text{cl}}^3 m_{\text{H}}] \simeq 1 \times 10^4 \text{ cm}^{-3}$ where $M_{\text{gas}} = Nm_*\eta_{\text{SF},0.1}^{-1} = 5 \times 10^4 M_{\odot}$ given $m_* = 10M_{\odot}$ and $\eta_{\text{SF},0.1}$ is the star formation efficiency in units of 0.1; i.e., 10% of the gas in the cloud is used to form massive stars. This density is comparable to those in typical dense cores in star forming regions (e.g., $n_{\text{H}} \sim 10^4 \text{ cm}^{-3}$; e.g., Lada, Strom, & Myers 1993). Note that the gas mass lies in the observed range of M_{GMC} . The mass volume density of massive stars is estimated as $Nm_* / [(4\pi/3)r_{\text{cl}}^3] \simeq 22M_{\odot} \text{ pc}^{-3}$. This is lower by two orders of magnitude than that of the compact star cluster R136a, whose half light radius is 1.7 pc, embedded in the central region of the 30 Dor nebula in Large Magellanic cloud; $5.5 \times 10^4 M_{\odot} \text{ pc}^{-3}$ (Hunter et al. 1995). Therefore, the star formation properties as well as the star cluster properties in our model are not unusual.

Finally we mention which type of galaxies tends to have more massive IMBHs. Using equations (1) and (2) together with the relation $M \sim Rv_{\text{rot}}^2/G$, we obtain

$$\tau_{\text{dyn}} \sim \frac{N}{2} \frac{R}{v_{\text{rot}}} \sim \frac{N}{2} \frac{\tau_{\text{rot}}}{2\pi}, \quad (3)$$

where τ_{rot} is the rotation period. If the rigid rotation is achieved up to a radius of $R = 1 \text{ kpc}$ as observed, the dynamical timescale is independent of R if $R \leq 1 \text{ kpc}$; i.e., any cluster of compact remnants left from the core of a giant H II region within $R \leq 1 \text{ kpc}$ could evolve to an IMBH. Since any disk galaxy have been able to form such IMBHs during its lifetime, i.e., $\sim 10^{10}$ years, the total number of IMBHs formed in its lifetime is estimated to be

$$N \sim 4\pi \times \left(\frac{\tau_{\text{dyn}}}{\tau_{\text{rot}}} \right) \sim 4 \times 10^3 \left(\frac{\tau_{\text{dyn}}}{10^{10} \text{ y}} \right) \left(\frac{\tau_{\text{rot}}}{3.1 \times 10^7 \text{ y}} \right)^{-1}. \quad (4)$$

More importantly, the relation given in equation (3) implies that galaxies with slower rigid-rotation velocities (i.e., late-type spirals) tend to have less massive IMBHs while those with higher rigid-rotation velocities (i.e., early-type spirals) tend to have more massive IMBHs. Since the survey conducted by CM99 is biased to late-type spirals, we are unable to make this observational test. X-ray surveys will be recommended for a sample of early-type spirals to test whether or not this prediction is consistent with observation.

2.2. Intermediate-mass Black Holes Supplied from Satellite Galaxies

We have shown that an IMBH can be made through the merger of compact remnants of massive stars born in a giant H II region. Since any galaxies have satellite galaxies (e.g., Zaritsky et al. 1997) and giant H II regions could be made in some gas-rich satellites (e.g., 30 Dor in LMC), it seems important to investigate a possibility that

IMBHs can be supplied by minor mergers with satellite galaxies having IMBHs. M 32, one of the satellite galaxies of M 31, may have a supermassive black hole with a mass of $\sim 10^6 M_\odot$ (Dressler & Richstone 1988; see for a review Kormendy et al. 1998). At present, there is no observational evidence for the presence of IMBHs in any satellite galaxies. However, if some satellite galaxies had IMBHs in their nuclei, it could be possible that minor mergers with such satellites are responsible for the presence of IMBHs in circumnuclear regions of the host galaxies.

We estimate the frequency of occurrence of compact X-ray sources if all of them are attributed to the IMBHs supplied by minor mergers with nucleated satellite galaxies (see Taniguchi & Wada 1996). Tremaine (1981) estimated that every galaxy would experience minor mergers with its satellite galaxies several times. Since a typical galaxy may have several satellite galaxies, the probability of merger for a satellite galaxy may be estimated to be $f_{\text{merger}} \simeq 0.5$; i.e., half of the satellite galaxies have already merged to a host galaxy, while the rest are still orbiting. Another important value is the number of nucleated satellite galaxies. For example, M31 has two nucleated satellites (M32 and NGC 205), and a field S0 galaxy NGC 3115 has a nucleated dwarf (van den Bergh 1986). Although there has been no systematic search for nucleated satellite galaxies, it is likely that every galaxy has (or had) a few nucleated satellites. Therefore, for simplicity we assume $n_{\text{sat}} = 2$. If we assume that the typical lifetime of the X-ray sources is $\tau_{\text{active}} \simeq 10^8$ years, we obtain an expected frequency,

$$P_{\text{IMBH}} \simeq f_{\text{merger}} n_{\text{sat}} \tau_{\text{active}} \tau_{\text{Hubble}}^{-1} \sim 0.01 n_{\text{sat},2} \tau_{\text{active},8}, \quad (5)$$

where τ_{Hubble} is the Hubble time, $\sim 10^{10}$ years, $n_{\text{sat},2}$ is the number of nucleated satellites in units of 2, $\tau_{\text{active},8}$ is the duration of the active phase in units of 10^8 years. Hence, if minor mergers with nucleated satellites are responsible for the IMBHs in the circumnuclear regions of their host galaxies, it is statistically expected that hard X-ray sources are found in about 1 % of field disk galaxies. This is significantly smaller than the observed frequency, $\gtrsim 50\%$ (CM99).

However, it seems possible that IMBHs can be formed through the dynamical relaxation of cores of giant H II regions in gas-rich satellite galaxies and they travel to circumnuclear regions of their host galaxies by minor mergers. This case gives another expected frequency,

$$P_{\text{IMBH}} \simeq f_{\text{merger}} n_{\text{sat}} n_{\text{IMBH}} \tau_{\text{active}} \tau_{\text{Hubble}}^{-1} \quad (6)$$

where n_{IMBH} is the number of IMBH in each satellite galaxy. Since the maximum number of IMBHs can be estimated

as $n_{\text{IMBH}} \sim \tau_{\text{Hubble}}/\tau_{\text{dyn}}$, we obtain

$$P_{\text{IMBH}} \simeq f_{\text{merger}} n_{\text{sat}} \tau_{\text{active}} \tau_{\text{dyn}}^{-1} \sim 0.1 n_{\text{sat},2} \tau_{\text{active},8} \tau_{\text{dyn},9}^{-1} \quad (7)$$

where $\tau_{\text{dyn},9}$ is the dynamical timescale in units of 10^9 years. Note that n_{sat} is not the number of nucleated satellites but that of gas-rich satellites. However, for simplicity, we adopt $n_{\text{sat}} = 2$ even in this estimate.

In summary, the frequency of occurrence of IMBHs supplied from satellite galaxies lies in a range between 0.01 and 0.1. Therefore, we suggest that minor mergers may not explain the observed higher frequency of IMBHs unless $n_{\text{sat}} > 10$.

3. Alternative Mechanisms

We have shown that continual merging of compact remnants left from massive stars in a giant H II region formed in circumnuclear regions of galaxies may be responsible for the formation of an IMBH intermediate-mass black hole within a timescale of $\sim 10^9$ years. A necessary condition is that several hundreds of massive stars are formed in a compact region with a radius of a few pc. In this section, we discuss some alternative mechanisms responsible for the formation of IMBHs.

3.1. Bondi-type gas accretion onto a seed black hole

Compact remnants left from massive stars formed in the initial star formation in a galaxy have been surviving for the galaxy age, i.e., $\tau_{\text{age}} \sim 10^{10}$ years. They have been experiencing a number of encounters with gas clouds in the galaxy. Therefore, classical Bondi-type (Bondi 1952) gas accretion is the most probable accretion process for them (Yoshii 1981). This gas accretion rate is given by $\dot{M}_{\text{Bondi}} = 2 \pi m_{\text{H}} n_{\text{H}} r_{\text{a}}^2 v_{\text{e}}$, where m_{H} , n_{H} , r_{a} , and v_{e} are the mass of a hydrogen atom, the number density of the hydrogen atom, the accretion radius defined as $r_{\text{a}} = GM_{\bullet} v_{\text{e}}^{-2}$ (M_{\bullet} is the mass of the seed compact remnant), and the effective relative velocity between the seed black hole and the ambient gas, respectively.

Since the Bondi-type gas accretion is most important for the low-velocity encounter, we adopt $v_{\text{e}} = 1 \text{ km s}^{-1}$ in order to estimate the maximum accretion rate (Yoshii 1981) although v_{e} is realistically much higher than this value. Adopting an average gas density of the interstellar medium, $n_{\text{H}} \sim 1 \text{ cm}^{-3}$, we obtain the total accreting mass due

to the Bondi-type accretion,

$$M_{\text{acc,Bondi}} = \dot{M}_{\text{Bondi}} \tau_{\text{age}} \sim 3 \times 10^{-2} M_{\bullet,1}^2 n_{\text{H},1} v_{\text{e},1}^{-3} \tau_{\text{age},10} M_{\odot} \quad (8)$$

where $M_{\bullet,1}$ is the mass of the seed compact remnant in units of $1M_{\odot}$, $n_{\text{H},1}$ is the average gas density in units of 1 cm^{-3} , $v_{\text{e},1}$ is the orbital velocity with respect to the ambient gas in units of 1 km s^{-1} , and $\tau_{\text{age},10}$ is the age of the galaxy in units of 10^{10} years. Even if a black hole with a mass of $10 M_{\odot}$ was born 10^{10} years ago in the galaxy (see for the formation of black holes with $m_{\bullet} \simeq 10M_{\odot}$, Brown & Bethe 1994), its accreting mass amounts only to a few M_{\odot} . It is expected that some black holes might encounter dense molecular clouds. However, the crossing time is as short as $\tau_{\text{cross}} \sim D_{\text{GMC},45}/v_{\text{e},1} \sim 4.5 \times 10^7$ years where $D_{\text{GMC},45}$ is the mean diameter of GMCs in units of 45 pc. It is also noted that the age of a GMC may range between $\sim 10^5$ years (the molecule formation time) and several times 10^8 years (e.g., Elmegreen 1985). Therefore, in the case of an encounter between a black hole and a GMC, we should adopt $\tau_{\text{age}} \sim 10^8$ years in equation (8). Therefore, the mass growth is negligibly small even if $\bar{n}_{\text{H}} \sim 50 \text{ cm}^{-3}$. However, if $v_{\text{e}} \ll 1 \text{ km s}^{-1}$, an IMBH could be formed through this accretion process. Since it seems unlikely that such a very slow encounter occurs frequently, it is suggested that the Bondi-type gas accretion onto the seed black hole may not be responsible for the formation of an IMBH within the age of the galaxy.

3.2. Disk-type gas accretion onto a seed black hole

Next we consider a case that a compact remnant is a black hole with a mass of $1 M_{\bullet}$ and the disk-type gas accretion has been occurring at the Eddington accretion rate, $\dot{M}_{\text{Disk}} \simeq 2.2 \times 10^{-8} \eta_{\text{acc},0.1} M_{\bullet,1} M_{\odot} \text{ y}^{-1}$ where η_{acc} is the conversion efficiency from the gravitational energy to the radiation in units of 0.1 (e.g., Rees 1984). The seed black hole with a mass of $1 M_{\odot}$ can increase in mass and its mass is given by

$$M_{\bullet}(t_8) = M_{\bullet,1} e^{2.2\eta_{\text{acc},0.1} t_8} M_{\odot} \quad (9)$$

where t_8 is the duration of the gas accretion in units of 10^8 years. One obtains $M_{\bullet} = 10^2 M_{\odot}$ at $t_8 = 2.09$, $M_{\bullet} = 10^3 M_{\odot}$ at $t_8 = 3.14$, and $M_{\bullet} = 10^4 M_{\odot}$ at $t_8 = 4.19$. Therefore, it seems that IMBHs could be easily formed by this mechanism.

However, there is a serious problem in this model. The star formation rate may be higher in earlier phases of galaxy evolution. Even if we assume that massive stars have been made continuously at a constant rate, the number of compact remnants made during the last 10^9 years is estimated to be $\sim 10^7$ for a typical galaxy with mass of

$10^{12}M_{\odot}$ in which stars were formed with the Salpeter mass function (see Taniguchi et al. 1999). If all these compact remnants have been experiencing the disk accretion at the Eddington rate, we would observe a lot of IMBHs in the galaxy if they have not yet merged into one SMBH. If they were already merged into one SMBH, there would be a very supermassive black hole with mass of $M_{\bullet} \sim 10^7 \times 10^4 M_{\odot} \sim 10^{11} M_{\odot}$ in some galaxies. Therefore, the idea described here may not be a dominant mechanism responsible for the formation of IMBHs.

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