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Letter to the Editor

# Growth of supermassive black holes and metallicity in quasars

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**Abstract.** The strong correlation between the mass of the central supermassive black hole (SMBH) and the bulge in some galaxies and quasars implies that the formation of the black hole is somehow linked to the bulge. The measurement of metallicity by NV/CIV or NV/HeII in quasars allows to discuss a possible way of formation of the black hole. In this letter we trace the metallicity along the possible routes in Rees' diagram in order to test the ways by which SMBHs can form. We derive a relation between the metallicity and the mass of the SMBH as $Z \propto M_{\rm BH}$ based on the numerical simulation of the evolution of star clusters. It is in good agreement with the relation determined by the metallicity measured by NV/CIV or NV/HeII in Hamann & Ferland's sample. This lends observational support to the formation of SMBHs via routes R4 or R5, namely, the evolution of dense star clusters.

**Key words.** black hole – metallicity – quasars

## 1. Introduction

There is increasing evidence for the presence of supermassive black holes (SMBHs) in the centres of galaxies and quasars from current observations (see the reviews of Rees 1984; Richston et al. 1998; Kormendy & Gebhardt 2001). The masses of SMBHs in galaxies strongly correlate with the masses of the corresponding bulges (Magorrian et al. 1998), and even stronger with the dispersion velocity (Gebhardt et al. 2000). These facts reflect that the SMBHs grow with the bulges, albeit in a way which is yet unknown (Burkert & Silk 2001). The finding of the relation of Magorrian et al. (1998) may give us a clue to understand how SMBHs are formed in galaxies. Laor (1998) originally realized that there is a similar relation between the masses of SMBHs and the bulge luminosities of their host galaxies in 14 bright quasars (for active galactic nuclei see Wandel 1999, Ferrarese et al. 2001). In Laor's sample, SMBH masses are measured by the velocity dispersion of the H$\beta$-emitting clouds, and the bulge luminosities are from *Hubble Space Telescope* (*HST*) observations. These relations are connected to the growth of the SMBHs. However, how exactly a black hole grows, remains open.

Rees (1984) gave a map of all possible routes of SMBH formation. There are mainly two possible ways to form the central SMBH (see the routes of SMBH formation in Rees' diagram). The first is that SMBH forms directly from the primordial gas cloud, this is further investigated by Loeb (1993), Loeb & Rasio (1994). The physical reason is that star formation would be quenched when the infalling primordial gas reaches some critical central concentration (Loeb & Rasio 1994). On the other hand, a dense star cluster may be formed via star formation. This is supported by the observations of nearby galaxies showing that there is a central star cluster with density of $\sim 10^6 - 10^8\ M_\odot$ and a one dimensional velocity dispersion $\sigma$ of typically $\sim 100 - 400$ km s$^{-1}$ (Lauer 1989). The dense star cluster will inevitably form a SMBH, although the stars may evolve in somewhat different ways (Begelman & Rees 1978; Duncan & Shapiro 1983; Quinlan & Shapiro 1987).

It has been argued that three parameters, such as the mass and the spin of the black hole, and the accretion rate, may give a full description of a quasar (Blandford 1990). Recently, the metallicity, has received attention as the fourth parameter. It has become evident that quasars have very high metallicity, even at very high redshift ($z > 4$) (Hamann & Ferland 1999). This means that there must have been very rapid and violent stellar evolution in the early stages of these quasars to produce the high metallicity (Haehnelt & Rees 1993). Metallicity, as a possible consequence of the formation and growth of SMBHs, may provide invaluable information of the history of quasars (Hamann & Ferland 1999).

We are motivated by the chemical evolution of quasars based on measurements of metallicity (Hamann & Ferland 1992, 1993) to investigate this subject. The observation of

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emission line spectra of quasars can, in principle, provide the abundances in the broad line region (BLR), and would allow to deduce the details of the chemical evolution of the corresponding nucleus since the BLR is the innermost part of a quasar. In this Letter, we make an attempt to trace the metallicity of every route in Rees' diagram, and naturally connect the growth of the SMBH to the observed metallicity in quasars.

## 2. Observational metallicity in quasars

High metallicity is common among quasars. As an independent parameter describing quasars, metallicity may be used to trace the evolutionary history of quasars. The metallicity in quasars may open a new way to understand the growth of a SMBH. It has been suggested by Hamann & Ferland (1993) that NV/CIV or NV/HeII are very good indicators of the metallicity in quasars. They subsequently measured the metallicity in a large sample of quasars (Hamann & Ferland 1993, 1999). There appears unambiguous evidence for a correlation between metallicity and luminosity. Although we do not fit this correlation via regression, it is found that

$$\left(\frac{\mathrm{NV}}{\mathrm{CIV}}\right) \propto (\nu L_\nu)^{\alpha_1}, \quad \text{or} \quad \left(\frac{\mathrm{NV}}{\mathrm{HeII}}\right) \propto (\nu L_\nu)^{\alpha_2}, \tag{1}$$

where $\alpha_1 \approx \alpha_2 \approx 0.5$, and $L_\nu$ is the specific luminosity at frequency $\nu$. The reverberation technique provides a set of available data of quasars (Kaspi et al. 2000), and shows a relationship between the mass of a black hole and its luminosity $M_{\rm BH} \propto (\nu L_\nu)^\beta$ with $\beta \approx 0.5$. From the above relations, we have

$$\left(\frac{\mathrm{NV}}{\mathrm{CIV}}\right) \propto M_{\rm BH}^{\alpha_1/\beta}, \quad \text{or} \quad \left(\frac{\mathrm{NV}}{\mathrm{HeII}}\right) \propto M_{\rm BH}^{\alpha_2/\beta}. \tag{2}$$

This relation is mainly derived observationally, and the only assumption is that the BLR clouds are virialized in the potential of the SMBH. It is generally believed that this approximation works in quasars (Netzer 1990).

## 3. Metallicity in Rees' diagram

Rees (1984) lists the possible ways to form SMBHs in the universe. There are five possible routes. Route 1 (R1) is collapse and/or accretion directly from an original gas cloud. Route 2 (R2) is through post-Newtonian instability of a supermassive star. The supermassive star may be formed through two possible ways: 1) direct collapse from a gas cloud, 2) from collisional disruption of stars in a dense star formed from the gas cloud. Route 3 (R3) is the merger of a black hole binary formed from the supermassive star induced by bar-mode instability. Route 4 (R4) means that a SMBH is born through spectacular accretion in a cluster of neutron stars or stellar-mass black holes. Route 5 (R5) suggests that a SMBH is formed in a relativistic cluster of compact objects as in R4, but the relativistic instability or gravitational radiation will induce the formation of SMBH.

First we check route 1 (R1). This route was studied by Loeb & Rasio (1994). In such a scenario, the SMBH is formed directly due to a catastrophic collapse or it grows via gradual accretion. As we show below, a supermassive black hole may be formed via a single catastrophic collapse, but without ejection of metals since the gravitational binding energy is too strong to eject matter. Thus there will be no relation between metallicity and the mass of the black hole.

A supermassive star is first formed via two possible ways before collapsing to a SMBH. According to R2 a SMBH will be formed due to a post-Newtonian instability, R3 suggests that the SMBH is formed due to the merger of binary black holes. This process will lead to huge radiation of gravitational waves. It may be confirmed by the detection of gravitational radiation. The two routes (R2 and R3) employ the formation of a supermassive star. Here we will show that there is an upper limit for the mass of a SMBH created via R2.

The structure and evolution of the supermassive star is insufficiently understood. We assume that the supermassive star is composed of hydrogen. The gravitational binding energy of an object with mass $M$ and radius $R$ is $E_{\rm g} \approx GM^2/R$, where $G$ is the gravitational constant. Its total nuclear energy is $E_{\rm n} = \epsilon Mc^2$ with $\epsilon$ being the conversion efficiency ($\epsilon = 0.007$ for the burning of hydrogen to helium) and $c$ is the speed of light. If we adopt the mass-radius relation $R = R_0\,(M/M_\odot)^q$ for supermassive stars, where $R_0 = 9.0 \times 10^{11}$ cm and $q = 0.47$ (Collins 1989), we will have the upper limit of the mass of the supermassive object ejecting matter during the supernova explosion

$$\frac{M_{\rm c}}{M_\odot} = (2\epsilon)^{1/(1-q)}\left(\frac{c}{v_0}\right)^{2/(1-q)} = 4.5 \times 10^6, \tag{3}$$

based on $E_{\rm g} \leq E_{\rm n}$, where $v_0 = (G\,M_\odot/R_0)^{1/2}$. No mass ejection takes place during the formation of the black hole, albeit the collapse of the supermassive star for $M \geq M_{\rm c}$. If a SMBH forms directly from the collapse of a primordial gas cloud, as the mass of SMBH is much higher than $M_{\rm c}$, the detectable metallicity may be low because (1) no heavy elements produced in the collapse have been ejected, and (2) the dominance of radiation pressure in supermassive stars and compact supermassive disks would prevent fragmentation and star formation in these systems (Loeb 1993; Loeb & Rasio 1994). Although a strong wind may developed from the suface of supermassive star, the first reason (1) is still supported by the fact that the timescale of contraction of the supermassive star is much shorter than that of the mass loss through the wind on the surface of supermassive star. The contraction timescale of a supermassive star approximates to $t_{\rm contr} \approx 3 \times 10^3 R_{14}(M/M_{\rm c})^{1/2}$ yr, where the typical dimension of the supermassive star $R_{14} = R/10^{14}$ cm (Fricke 1973). This timescale is much shorter than the mass loss timescale $t_{\rm w} = M_{\rm c}/\dot{M} \approx 10^{10}(M/M_{\rm c})$ yrs (Bond et al. 1984). Therefore there is no significant ejection of metals during the rapid evolution of the supermassive star.

It has been argued that the collision between a normal galaxy and a naked SMBH leads to the activity in a galaxy (Fukugita & Turner 1996), but in this case there is no correlation between metallicity and the mass of SMBH. On the other hand, if a SMBH is formed in a dense star cluster via coalescence of stars or by a merger of stellar mass black holes, there is an approximate proportional relationship between the metallicity and the mass of the SMBH according to the dynamical and stellar evolution of the cluster. We will derive a crude approximation about this relation below.

Routes 4 and 5 (R4 and R5) suggest that the SMBH is formed in a dense star cluster. In R4 and R5, a cluster with stars heavier than 100 $M_\odot$ is formed in advance. The high rate of supernova explosions leads to the formation of a cluster of neutron stars or steller-mass black holes. We assume that some of the ejected medium from the supernova explosions may form clouds in the broad line region. The two ways have a rough metallicity prediction as we show in the following. Following Duncan & Shapiro (1983), we assume that the cluster consists of $N = 10^8 N_8$ stars with a dispersion velocity $v = 350 v_{350}$ $(\mathrm{km\,s^{-1}})$, this star cluster thus has a core with a radius $R_\mathrm{c} = 2.3 N_8 v_{350}^{-2}$pc. Out of the radius $R_\mathrm{c}$, the initial density has a power law profile $n(r) \propto r^{-p}$, here $p$ is the index. This power law distribution may work further into the kilo parsec scale bulge (Balcells 2001). The two-body relaxation time is $t_\mathrm{r} = 1.5 \times 10^{10} N_8 \Lambda_{18}^{-1} v_{350}^{-3}$ yr, where $\Lambda_{18} = \ln(0.5N)/18$ and the initial masses of all stars are taken as one solar mass $m$. The total mass and the collision time scale of star cluster are $mN$ and

$$t_\mathrm{coll} = 6.8 \times 10^{10} N_8^2 v_{350}^{-5} (1 + 1.3 v_{350}^2)^{-1}\ \mathrm{yr}, \tag{4}$$

respectively. The black hole grows due to the coalescence of stars via collision and tidal capture of stars because the collisional interactions are inelastic. Detailed numerical simulations show that the growth of a black hole can be divided into two phases for an isothermal sphere of solar type stars in the absence of a black hole (Duncan & Shapiro 1983):

$$\dot{M}_\mathrm{BH}(M_\odot\ \mathrm{yr}^{-1}) = \begin{cases} g_0, & \text{for}\ \ 0 \le t \le t_\mathrm{coll} \\ g_0 t^{-\gamma}, & \text{for}\ \ t \ge t_\mathrm{coll}, \end{cases} \tag{5}$$

where $g_0$ is a constant related to $N_8$ and $v_{350}$, $\gamma = (3 - 2p)/p \approx (0.9 \sim 1.0)$ is the growth index in the later phase weakly depending on the cluster parameters. For example, $g_0 \approx 1.7$, $\gamma = 1$ and $t_\mathrm{coll} = 2.0 \times 10^8$ yr for the case of $N_8 = 2.7$, $v_{350} = 2.9$ (Duncan & Shapiro 1983). Here we neglect the small peak of $\dot{M}_\mathrm{BH}$ around the critical time $t_\mathrm{coll}$. After the collisional phase the growth of the black hole is mainly via the capture of stars from the cluster. It is thus expected that the main phase of metallicity enrichment is within the the time $t_\mathrm{coll}$.

The Kelvin-Helmholtz time scale approximates to $t_\mathrm{KH} \approx 3.0 \times 10^7 (m/M_\odot)^{-2}$ yr, which represents the time scale to form a new star after coalescence (Quinlan & Shapiro 1987). Numerical results show that a massive star with about 50 $M_\odot$ can grow within a time scale $t_\mathrm{coal} \approx 10^6$ yr due to colliding star coalescence if the dispersion velocity is less than its escape velocity (Colgate 1967). The maximum mass of a star due to coalescence via collision can be estimated from the fact that the coalescence process saturates when an ordinary 1 $M_\odot$ star cannot be captured by the coalescencing star since this star can pass straight through them. Supposing the mass-radius relation to be $r^*/R_\odot = (m^*/M_\odot)^{3/4}$, we have

$$m^*_\mathrm{max} \le \left(\frac{v}{v_\mathrm{esc}}\right)^8 M_\odot = 53 \left(\frac{v_{350}}{2.9}\right)^8 M_\odot, \tag{6}$$

where $v_\mathrm{esc} = (2G\,M_\odot/R_\odot)^{1/2}$. This mass limit is sensitive to the dispersion velocity. Considering some other physical rules, the coalescencing stars may grow up to $50 \sim 100$ solar mass (Begelman & Rees 1978).

The time scale for star evolution approximates to $t_\mathrm{evo} = 6.0 \times 10^6 (50\ M_\odot/M)$ yr for stars larger than 12 $M_\odot$. $t_\mathrm{KH}$ is much shorter than the coalescence and evolution time scales of massive stars. It appears that the solar mass stars in the cluster may form many massive stars following the collisions and coalescence within the collision time scale. Once a massive star forms, the ejection of metal-rich ejecta will follow the post-main sequence nuclear burning, culminating most probably in a type II supernova. The heavy ($Z > 6\ Z_\odot$) element mass $M_z$ yield in ejecta varies with the progenitor mass, but is expected to be in the range of $4 \sim 40\ M_\odot$ (Woosley & Weaver 1986). The rapid rotation of the progenitor can modify the metal yield by a modest amount as shown by the calculations (Bodenheimer & Woosley 1983). Although it remains uncertain, the most likely remnants of massive progenitors are stellar-mass black holes with $\sim$10 solar mass (Woosley & Weaver 1986). Considering that the life time of a massive star is much shorter than the collisional time scale, the total mass of metals produced by supernova explosion is about $M_z = m_z\,(\mathrm{d}N/\mathrm{d}t)\,t$, then the metal abundance $Z$ can be obtained by,

$$Z \approx \left(\frac{m_z}{m}\right)\left(\frac{1}{N}\frac{\mathrm{d}N}{\mathrm{d}t}\right) t = \left(\frac{m_z}{m}\right)\left(\frac{t}{t_\mathrm{coll}}\right). \tag{7}$$

Combining Eqs. (5) and (7) we obtain the following relation between the mass of a growing black hole and the metallicity as

$$Z = \frac{1}{g_0 t_\mathrm{coll}}\left(\frac{m_z}{m}\right) M_\mathrm{BH}, \quad \text{for}\ \ 0 \le t \le t_\mathrm{coll}. \tag{8}$$

When $t \ge t_\mathrm{coll}$, as the growth of the SMBH is dominated by the capture of stars, the above relationship will not hold. Detailed numerical calculations using a photoionization model show that the abundance $Z$ is roughly proportional to the two ratios,

$$Z \propto \left(\frac{\mathrm{NV}}{\mathrm{CIV}}\right)^{\gamma_1}, \quad \text{or}\ \ Z \propto \left(\frac{\mathrm{NV}}{\mathrm{HeII}}\right)^{\gamma_2}, \tag{9}$$

and $\gamma_1 \approx \gamma_2 \approx 1$ measured from the right panel in Fig. 6 of Hamann & Ferland (1999). We would like to point out that this result is based on a series of broad emission line simulations that hold all other parameters fixed while the abundances are varied. We should keep this in mind. Thus the observable metallicity is given by

$$\left(\frac{\rm NV}{\rm CIV}\right) \propto M_{\rm BH}^{1/\gamma_1}, \quad \text{or} \quad \left(\frac{\rm NV}{\rm HeII}\right) \propto M_{\rm BH}^{1/\gamma_2}. \tag{10}$$

This formula works within the collisional timescale $t_{\rm coll}$ which is determined by the cluster itself. We find that the theoretical prediction (10) is in good agreement with the observational relation (2). Therefore routes 4 and 5 (R4 and R5) may be the likely ways to form a SMBH from a primordial gas cloud.

## 4. Conclusions and discussions

In this paper we trace the metallicity along the routes in Rees' diagram in order to test the possible ways by which SMBHs form in quasars. The argument that a single collapse of a supermassive star forms a SMBH is not supported by the observed relation between metallicity and luminosity in quasars. The reason is that the mass is too high for the ejection of metals since its self-gravitation energy is larger than the energy of nuclear reaction. We derive a formula of growth of a black hole with metallicity, which is in good agreement with the observed relation between metallicity and luminosity. Thus observations seem to support the formation of SMBHs from a dense star cluster via coalescence and evolution of stars.

There is a modified route 1 (hereafter MR1) suggested by the referee. It states that if stars form during the collapse, they will enrich the gas with metals before the formation of the central SMBH. The gas that forms the SMBH might be processed by a generation of stars in the host galaxy before it gets funneled into the core to make the SMBH. Such a complex formation of SMBH depends on many processes, fragmentation of cloud during the collapse, the formation of multi-generations of stars. Let us speculate that a primordial gas cloud with mass of several $10^8\ M_\odot$ is gravitationally fragmentized into several hundreds of massive stars with mass less than $4.5\times10^6\ M_\odot$. These massive stars evolve undergoing hydrogen burning, then eject metals due to supernovae explosion, leaving a cluster with several hundreds of intermediate mass black holes ($<10^6\ M_\odot$). What's the observational consequence of such a cluster? This interesting route will be explored in the future.

Recently, much attention has been given to the recurrent activity model of quasars (Haehnelt & Rees 1993), which seems to be supported by observations (Kuhn et al. 2001). The mass growth of a SMBH in the first generation of quasars may be mainly due to R4 or R5. The masses of SMBHs in recurrent quasars may not increase significantly in the subsequent generations within the Eddington timescale $M_{\rm BH}/\dot{M}_{\rm Edd} \approx 5.0\times10^8$ years. This argument might be supported by the fact that the relation of the SMBH mass with the bulge mass in quasars (Laor 1998) is similar to the Magorrian et al. relation in galaxies. We note that the slope of the relation found by Laor (1998) is slightly different from that of the Magorrian et al. relation. If the differences are real, we might then deduce the evolution of SMBH accretion after the first generation. This is worthy of a future investigation.

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