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Hypermassive Black Holes Shine in the Universe including the Childhood Universe

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Based on the general polytropic hydrodynamic formalism of self-similar gravitational collapse with spherical symmetry, we study the self-similar dynamic formation of black holes (BHs) in several astrophysical and cosmological contexts such as stellar mass BHs (sMBHs), intermediate mass BHs (IMBHs), supermassive BHs (SMBHs) and hypermassive BHs (HMBHs) – the latter two in the early Universe are of special interest here. We invoke the Paczynski-Wiita gravity to capture the key effects of general relativity and show the growth of BHs including SMBHs and HMBHs can be very rapid and effective in sufficiently massive host halos within timescales shorter than the Universe age of ~ 13.8 billion years. The effective pressure in our hydrodynamic formalism can represent that of gas in stars, that of random stellar motions in globular clusters, in bulges of spiral galaxies, and in elliptical galaxies, that of random galaxy motions in clusters of galaxies and that of random motions of dark matter (DM) particles as well as that of combinations of various pertinent components (including turbulence). In particular, we have predicted in 2013 that HMBHs in the mass range of $\sim 10^{10}-10^{12}M_{\odot}$ or larger can exist in the Universe and even in the early Universe in the forms of hard X-ray/gamma-ray sources or quasars [1]. We discuss several observational evidence for pertinent aspects and classifications and further speculate the possibility of DM BHs (DMBHs) and mixed matter BHs (MMBHs) in reference to the Bonnor-Ebert critical equilibrium condition with two tentative observed candidates. Based on the three-dimensional perturbation analysis of a spherical dynamic collapse [2, 3], certain internal gravity modes (g-modes) and all vorticity modes (v-modes) are unstable, implying inevitable turbulent massive motions during a dynamic collapse of forming a BH. Physical consequences including gravitational wave emissions, magnetohydrodynamic (MHD) dynamo processes, and acceleration of ultra-high energy cosmic rays (UHECRs) associated with such massive turbulence during dynamic collapses are also discussed. For the Southern African Large Telescope (SALT) further strengthened with infrared spectrometers, it is certainly capable of identifying quasars and ultra and extremely luminous infrared galaxies harboring SMBHs and/or HMBHs in the Universe including the early Universe. It would be of considerable interest to study the neutral hydrogen environments of SMBHs and HMBHs with increasing redshift z in a systematic manner.

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1. Introduction

After several decades, there is copious astronomical evidence for black holes (BHs) in various astrophysical systems such as sMBHs [4, 5, 6] most likely of stellar explosion origin, IMBHs in association with globular clusters [7], SMBHs in galactic bulges of spiral galaxies and in elliptical galaxies, and also HMBHs in the mass range of $\sim 10^{10}-10^{12}M_{\odot}$ and beyond [1, 8] – the last one is the highlight of this contribution especially in the early Universe. At the center of our own Galaxy, there exists a SMBH of $\sim 4\times 10^{6}M_{\odot}$ around the lower end of the SMBH mass range $\sim 10^{6}-10^{9}M_{\odot}$. How do these BHs form in general? In particular, how do these massive BHs such as SMBHs and HMBHs form in the Universe and even in the high-z early Universe? [9, 10] The prevalent view at present is that these massive BHs are formed via disk accretions and processes of merging smaller BHs [11, 12, 13]. For disk accretions, the difficulty is to remove angular momentum effectively so that BHs can grow sufficiently fast. To form more massive BHs by merging smaller BHs, the key issue is the merging frequency in the Universe. The results of several Pulsar Timing Array (PTA) experiments so far do not support this frequent merging hypothesis [14, 15, 16, 17].

Alternatively, we take the point of view that at least a considerable fraction of BHs are dynamically formed by direct gravitational collapse from massive host halos and/or reservoirs. There is evidence for likely BH mergers but they are not that frequent as constrained by several up-to-date PTA results [14, 15, 16, 17]. The initial spatial distribution of angular momentum within host halos and/or reservoirs can have various conceivable forms. Another important pertinent question would be the total angular momentum profile for massive halos and/or reservoirs in a broad range of masses during the evolution of our Universe. Numerical N-body simulations in proper contexts may provide useful hints[18, 19]. In figure 1 of reference [18], the numerical distribution (histogram) of the halo spin parameter and the analytical fitting expression (log-normal) deviate from each other at small and/or zero spin regime. Most likely, there is a relatively small yet sizable fraction of mass halos or reservoirs that have very small or almost no angular momentum. In a certain model consideration [20, 21, 22], the average angular momentum parameter for mass halos can be fairly small in the sense of very little systematic rotation and negligible rotational support. Within a mass halo, those materials with almost no angular momentum will overcome the effective pressure and collapse directly under self-gravity, while those materials with angular momentum would eventually form a rotating disk or torus during collapse. Such a disk/torus co-evolves with the dynamic system and can continue to accrete onto the central collapsed object by losing angular momentum. Moreover, disk accretions and activities provide various important and valuable diagnostics for detecting central BHs and surrounding rotating disks.

In this contribution, we mainly focus on general polytropic (GP) spherical hydrodynamic collapses with the Pazcynski-Wiita gravity [23] to dynamically form BHs including SMBHs and HMBHs among others. We present the theoretical predictions for HMBHs in the early Universe and describe pertinent observational evidence. Based on the static Bonnor-Ebert critical equilibrium model framework, we also advance the hypothesis of dark matter BHs (DMBHs) and mixed matter BHs (MMBHs) in the entire Universe including the early Universe. We also discuss inevitable massive turbulent motions during dynamic collapses and their possible physical consequences when magnetic fields are also involved, e.g., gravitational wave emissions, MHD dynamo processes, and acceleration of UHECRs.

With upgraded infrared spectrometers for the 10m Southern African Large Telescope (SALT), it would be both valuable and feasible to search, target, identify, confirm and analyze sources such as quasars, central cluster galaxies, and ultra and extremely luminous infrared galaxies where SMBHs and/or HMBHs can reside in deep gravitational potential wells of massive host halos.

2. General polytropic hydrodynamic formalism with Paczynski-Wiita gravity

The Paczynski-Wiita (P-W) potential was originally introduced for studying accretion disk dynamics [23]. As stated clearly, the main motivation was to catch the essence of general relativity (GR) yet to reduce mathematical complexity to a considerable extent. With the P-W potential, several key GR features are indeed retained in the context of accretion disks [24].

In our hydrodynamic collapse formalism of spherical symmetry, we invoke the P-W gravity in the exactly same spirit. The presence of an event horizon is natural now and the Schwarzschild radius $r_s = 2GM/c^2$ grows with time t due to a spherical mass collapse/accretion under self-gravity onto a central BH. In contrast to the formulation with the Newtonian gravity [25], a dimensionless parameter $s \equiv 2C_s^2/c^2$ now appears in the new formalism with the P-W gravity [1] where C_s is the (effective) sound speed or random (turbulent) velocity dispersion and c is the speed of light.

In spherical polar coordinates $(r,\ \theta,\ \phi)$, the ideal nonlinear hydrodynamic partial differential equations (PDEs) for a spherically symmetric evolution of a GP gas or fluid are given below

$$\frac{\partial\rho}{\partial t}+\frac{1}{r^2}\frac{\partial}{\partial r}(r^2\rho u)=0\ , \qquad \frac{\partial M}{\partial t}+u\frac{\partial M}{\partial r}=0\ , \qquad \frac{\partial M}{\partial r}=4\pi r^2\rho\ , \tag{2.1}$$

$$\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial r}=-\frac{1}{\rho}\frac{\partial p}{\partial r}-\frac{GM}{(r-2GM/c^2)^2}\ , \qquad \left(\frac{\partial}{\partial t}+u\frac{\partial}{\partial r}\right)\ln\left(\frac{p}{\rho^\gamma}\right)=0\ , \tag{2.2}$$

where $G = 6.67\times10^{-8}\mathrm{g}^{-1}\ \mathrm{cm}^3\ \mathrm{s}^{-2}$ is the gravitational constant and γ is the polytropic index of a dynamic fluid, ρ, M, p and u are the mass density, the enclosed mass within radius r at time t, the effective pressure and the radial bulk flow velocity, respectively, and the Pazcynski-Wiita gravity and the formal conservation of specific entropy along streamlines are invoked in PDE (2.2). By a self-consistent self-similar transformation for nonlinear PDEs (2.1) and (2.2) with $k = C_s^2$,

$$r=k^{1/2}t\,x\ , \qquad u=k^{1/2}v(x)\ , \qquad \rho=\frac{\alpha(x)}{4\pi Gt^2}\ , \qquad p=\frac{k\,\beta(x)}{4\pi Gt^2}\ , \qquad M=\frac{k^{3/2}t\,m(x)}{G}\ , \tag{2.3}$$

we derive two coupled nonlinear ODEs for $v(x)$ and $\alpha(x)$ with several valuable integrals [1].

We have obtained an asymptotic analytic solution at large x in the form of

$$v(x)=v_0+\left[2\alpha_0^{3\gamma-3}-\frac{\alpha_0}{(1-s\alpha_0)^2}\right]\frac{1}{x}+o\left(\frac{1}{x}\right)\ , \tag{2.4}$$

$$\alpha=\frac{\alpha_0}{x^2}\left\{1+\left[2\alpha_0^{3\gamma-3}-\frac{\alpha_0}{(1-s\alpha_0)^2}\right]\frac{1}{2x^2}\right\}+o\left(\frac{1}{x^4}\right)\ , \tag{2.5}$$

where v_0 and α_0 are two dimensionless integration constants and are referred to as the velocity and density parameters, respectively. We have also derived an asymptotic analytic solution approaching the event horizon x_s corresponding to $r_s = 2GM/c^2$. To the leading order near $x_s = sm_0$, this asymptotic analytic solution is

$$v=-\left(\frac{2m_0}{x-sm_0}+v_d^2\right)^{1/2},\qquad \alpha=\left[s^2m_0\left(\frac{2m_0}{x-sm_0}+v_d^2\right)^{1/2}\right]^{-1},\qquad r_s=\frac{2GM}{c^2}=2t\frac{C_s^3}{c^2}m_0\ , \tag{2.6}$$

where $v_d > 0$ is a dimensionless integration constant and $m_0 = -x^2\alpha v > 0$ is another dimensionless integration constant physically related to the enclosed mass within $x = x_s$ or the mass accretion rate there. Here, $x_s = sm_0$ (the last of equation (2.6)) corresponds to the expanding event horizon of a central Schwarzschild BH. By imposing these asymptotic analytic solutions and taking proper care of properties of the sonic critical curve, it is straightforward to numerically integrate the two coupled nonlinear ODEs in terms of $v(x)$ and $\alpha(x)$ using the standard Runge-Kutter scheme. Details of pertinent model analysis can be found in reference [1].

Using asymptotic solutions (2.4)−(2.6), we have readily constructed collapse solutions expanding into a static environment to determine the possible m_0 range. For $\gamma \leq 4/3$, there is always one such solution; while for $\gamma > 4/3$ and sufficiently small s ratio, there exist two such solutions – an interesting novel feature of P-W gravity [1]. By the last of solution (2.6), the larger the values of C_s and m_0, the faster the mass accretion rate and thus for a sufficiently long time duration t without interruptions, a massive BH would emerge eventually. For a sensible range of C_s, it is entirely feasible to grow HMBHs within 13.8 billion years in the range of $\sim 10^{10} - 10^{12} M_\odot$ or higher in the Universe including the early Universe as long as there are sustained and sufficiently large mass halos or reservoirs without accidental disruptions. Of course, a BH mass would be more or less set when accidental interruptions do occur. In this framework of scenarios, the dynamic formation of SMBHs in the mass range of $\sim 10^6 - 10^9 M_\odot$ should have no problem [25].

The recently detected ultraluminous quasar SDSS J010013.02+280225.8 with a BH mass of $1.2 \times 10^{10} M_\odot$ at $z = 6.3$ ($\sim 8 \times 10^8$ years after the Big Bang), surprising to many [9], falls around the lower end of our theoretically predicted mass range for HMBHs [1, 26]. Another “extremely luminous infrared galaxy" or ELIRG W2246-0526 of $z = 4.593$ from Wide-field Infrared Survey Explorer (WISE) sources has a bolometric luminosity of $L_{bol} \sim 3.5 \times 10^{14} L_\odot$ with an estimated BH mass of $\sim 3 \times 10^9 M_\odot$ [27] and thus lies around the higher end of the predicted mass range for SMBHs [1]. For X-ray-selected Active Galactic Nuclei (AGNs) with $z \sim 3$ to 4 in the Cosmic Evolution Survey field (COSMOS), an unobscured AGN CID-947 at $z = 3.328$ (~ 2 billion years after the Big Bang) was inferred to have a BH mass of $M_{\rm BH} = 6.9^{+0.8}_{-1.2} \times 10^9 M_\odot$ also around the higher end of SMBHs. The striking feature of CID-947 is the unusually high mass ratio $M_{\rm BH}/M_* \cong 1/8$ where M_* is the inferred host galaxy stellar mass [28]. So far only one local compact lenticular galaxy NGC 1277 ($\gtrsim 8 \times 10^9$ years) was reported to have a comparable $M_{\rm BH}/M_* \cong 1/7$ with $M_{\rm BH} = 1.7 \times 10^{10} M_\odot$ [29] which also lies around the lower end of the mass range for HMBHs [1]. As we shall discuss below, these two latter cases might involve DMBHs with relatively less normal matter around in the host galaxies yet in more massive DM halos. Other observed cases are described and discussed more recently by Lou and Hu [8]. For example, NGC1600, an isolated massive elliptical galaxy 64 Mpc away, hosts a $(1.7 \pm 0.15) \times 10^{10} M_\odot$ HMBH [30].

3. Observational evidence for HMBHs in the early Universe

Based on our model scenario of spherical GP dynamic collapse, the removal of angular momentum is not an issue at all and the growth of a collapsing or accreting BH can be very rapid and efficient within a fraction of the Universe age as long as there exists sustained sufficiently massive halos or reservoirs without interruptions. We therefore made a clear prediction that "Such GP spherical dynamic mass collapse is shown to be highly efficient for the rapid formation of supermassive black holes (SMBHs; mass range of $\sim 10^6 - 10^{10} M_\odot$) in the early universe or even hypermassive black holes (HMBHs; mass range of $\sim 10^{10} - 10^{12} M_\odot$) if extremely massive mass reservoirs could be sustained for a sufficiently long time, which may evolve into hard X-ray/gamma ray sources or quasars according to their surroundings" in MNRAS Advance Access publication on 2013 December 20 (http://mnras.oxfordjournals.org/content/438/2/1242.full.pdf) [1].

Remarkably, ten days later in the night of 2013 December 29, the initial optical spectroscopy on J0100+2802 was carried out with the Lijiang 2.4-m telescope in YunNan Province of China [26]. The Lyα break with a rest-frame wavelength of 1216 $\overset{\circ}{A}$ is clearly shifted to about 8800 $\overset{\circ}{A}$, consistent with a quasar at $z \gtrsim 6.2$. This was soon confirmed in the USA by the 6.5-m Multiple Mirror Telescope (MMT) and the twin 8.4-m mirror Large Binocular Telescope (LBT) on 2014 January 9 and 24, respectively. From an adopted empirical conversion, the bolometric luminosity is estimated to be $L_{bol} = 1.62 \times 10^{48}$ erg s$^{-1} = 4.29 \times 10^{14} L_\odot$ ($L_\odot = 3.846 \times 10^{33}$erg s^{-1} is the solar luminosity) which is the brightest for $z \gtrsim 6$ so far, e.g., 4 times brighter than that of the luminous $z = 6.42$ quasar SDSS J1148+5251, and 7 times brighter than that of the most distant known quasar ULAS J1120+0641 ($z = 7.085$). By combining the above data with the near-infrared J, H, K-band spectra acquired by the Gemini and Magellan telescopes in Chile on 6 August and 7 October 2014, respectively, this quasar BH mass is estimated to be $(1.24 \pm 0.19) \times 10^{10} M_\odot$.

This is the first evidence for the theoretically predicted HMBHs in the early Universe ($z \gtrsim 6$), even though there are other evidence for HMBHs at lower z [29, 30, 31]. Given selection effects, HMBHs and SMBHs should be actually more abundant than what we have detected so far. Their existence in the early Universe is an important revelation with broad implications. The current generation of $8 - 10$-m class telescopes (including the SALT with infrared spectrometers) has the capability to detect more such SMBHs and HMBHs at high redshifts and this would open up a completely new horizon. While more expensive, the next generation of $20 - 40$-m class telescopes and James Webb Space Telescope would reveal more in the even earlier Universe (Hubble Space Telescope reached $z = 11$) and detect clues of their host surroundings. There exists a strong selection effect: those of lower luminosity are very difficult to be detected in the early Universe. It is most likely that such HMBHs and SMBHs are dynamically formed by direct collapses which imply that a major mass fraction of a massive host halo or reservoir may have almost no angular momentum and the portion with angular momentum will give rise to a rotating disk during collapse by angular momentum conservation. In other words, disk accretions do not provide all the mass of central BHs during their lifetimes in a considerable fraction of cases. The association with accretion disks would help the detection of such central BHs. This scenario also poses considerable challenges of deriving statistics for spins of the claimed SMBHs and HMBHs both theoretically and observationally.

4. Merger issue of HMBHs and SMBHs: How frequent are BH merging processes?

Because of the notorious difficulty of removing disk angular momentum for an effective mass accretion to form SMBHs and HMBHs, it was thought to form numerous smaller BHs first and then merge them in order to have much larger BHs [11, 12, 13]. Of course, there are still thorny questions of how to form this many smaller BHs by disk accretions in the first place. Given that, to form a $\sim 10^{10}M_{\odot}$ BH from smaller BHs of $\sim 10^5-10^6M_{\odot}$, merging processes must have taken place $\sim 10^5-10^4$ times in the Universe. For smaller seed BHs, the merging frequency would be even higher. While there is evidence for two SMBHs being close to each other for likely merging inside two colliding galaxies, it is not entirely clear whether such merging processes would occur frequently enough in the Universe in order to produce much larger SMBHs and HMBHs. For SMBHs and HMBHs in the early Universe, the available time is even shorter for disk accretion and merging.

The merging of two massive objects (e.g. two BHs) will give rise to a burst of gravitational waves (GWs) [4, 5, 6]. Frequent merging processes as such would produce a background level of gravitational waves in the Universe. After years of search so far, observational results of the Pulsar Timing Arrays do not support this scenario (Ni 2015, private communications) [14, 15, 16, 17]. At this stage, the frequent merger scenario seems untenable and this situation is unlikely to change in the coming years of further PTA experiments for detecting background GWs.

5. Physical consequences of inevitable turbulence during dynamic collapses

For our GP hydrodynamic model formalism, it is possible to perform three-dimensional (3D) perturbation analysis for waves and instabilities associated with self-similar dynamic radial flows involving collapses and/or outflows [2, 3, 32, 33, 34, 35]. For 3D GP perturbations, the acoustic waves (the so-called p-modes) are stable; there are always unstable internal gravity modes (the so-called g-modes); and the vorticity modes (referred to as the v-modes) associated with the background radial dynamic collapse are always unstable [2, 3]. Unstable g-modes give rise to convection and unstable v-modes lead to enhanced circulation components transverse to the radial direction. Specific to self-similar dynamic collapses, unstable g-modes and v-modes would lead to inevitable convective and circulatory turbulence in the nonlinear regime. Over much larger scales, one may regard such a turbulent mass halo system as quasi-spherical. In the sense of mean-field averages for physical variables, our model scenario may be adapted for a quasi-spherial dynamic collapse. With this in mind, the effective pressure in our model formalism should include the turbulent pressure effect (due to enhanced random velocity) and the GP EoS would extend to a dynamic yet turbulent mass medium.

Several physical consequences follow this scenario of 3D massive turbulent flows during overall radial dynamic gravitational collapses to form BHs.

First, for a spherically symmetric collapse in the strict sense, one might concern about the intense radiation generated around the central region to completely stop the radial material infall, i.e., the so-called Eddington luminosity. With 3D convective and circulatory turbulence, the overall system remains grossly spherical, yet strong radiation can leak out through boundaries of turbulent cells. The average pressure associated with the strong radiation field may slow down the mass infall but will not stop it completely. In other words, the situation of the so-call super-Eddington luminosity is possible in this dynamic collapse scenario involving massive turbulence and violent relaxation. Observationally, there are examples of quasars with super-Eddington luminosity [26].

Secondly, when magnetized partially ionized gas medium is involved in dynamic collapses under self-gravity, such massive turbulence can sustain magnetohydrodynamic (MHD) dynamo processes in operation to rapidly enhance seed magnetic fields and create various magnetic activities. For example, for a magnetized partially ionized gas medium that is gravitationally coupled to the massive collections of stars and/or galaxies with DM halo involved in an overall gravitationally bound system, we may still invoke MHD for model conception. For smaller systems such as massive stars, a magnetized gas medium may be a major component, while for much larger systems such as globular clusters, galaxies and clusters of galaxies, it could be a minor component in terms of mass. Nevertheless, for turbulence induced by g-mode and v-mode instabilities during a dynamic collapse, the entanglement of magnetic fields would produce a whole range of physical effects. In the presence of large-scale converging shocks [36], magnetic fields in opposite directions can be drastically squeezed to make magnetic reconnection process very effective. Relativistic cosmic ray electrons traveling in entangled magnetic fields would give rise to synchrotron emissions. What we have in mind here is a whole range of grossly spherical astrophysical systems involving a very broad range of spatial scales.

Thirdly, among g-mode instabilities, one basic mode may be amplified giving rise to the initial kick of the central collapsed object, while among v-mode instabilities, one basic mode may be amplified corresponding to the spin of the central collapsed object [2]. Because of such an initial kick, a BH may be located away from the center of its host halo. Because of the spin and other unstable v-modes, Rossby-type waves can be generated to sustain gravitational wave emissions due to massive circulations during collapses [2, 37, 38, 39]. It is certainly of interest to search for such gravitational wave signals in association with dynamic formation of BHs.

6. Dark matter black holes (DMBHs) in the Universe

Presuming Newtonian gravity remains valid on large astronomical scales, astrophysical evidence over several decades for the existence of dark matter (DM) are very strong and this has stimulated world-wide efforts for actively searching DM particles in nearby space environment, on Earth in underground laboratories and in high-energy accelerators (e.g., Large Hadron Collider at CERN). Astrophysical inferences for the presence of considerable DM include galaxies, clusters of galaxies and the expanding Universe. Moreover, massive DM halos in relative isolation are inferred to associate with galaxies and clusters of galaxies and in extensive numerical simulations for cosmological large-scale structure formation. As we have assigned the gravitating property of DM and their ability to curve space-time the same as normal matter, the natural possibility of forming DMBHs in the central regions of spherical massive DM halos arises. According to our theoretical model formalism [1, 25], DMBHs can emerge dynamically in spherical gravitational collapses within sufficiently massive DM halos. Depending on the mass range of DM halos as well as DM properties, the mass range of DMBHs can be extremely broad – the higher end may well exceed $\sim 10^{12} M_\odot$ as long as sufficiently massive halos can sustain the uninterrupted supply of collapsing materials $-$ DM as well as normal matter.

For a spherically symmetric DM halo with self-gravity, let us invoke the Bonnor-Ebert model [40, 41] for an elaboration. The critical DM halo mass M is related to the critical radius R by

$$R = GM/(2.4a^2) , \tag{6.1}$$

where a is taken as the random velocity dispersion of DM particles within the massive DM halo and G is the gravitational constant. In reference to the Schwarzschild radius $r_s = 2GM/c^2$, this should put an upper limit for $a \lesssim c/\sqrt{5}$ in DM halos; otherwise, a DMBH would be there already. The related critical central DM mass density ρ_0 is then given by

$$\rho_0 = \left(\frac{2.4\xi_m a^2}{GM}\right)^2 \frac{a^2}{4\pi G} = (a/c)^6 (M/M_\odot)^{-2} 1.187 \times 10^{19} \text{ g cm}^{-3} , \tag{6.2}$$

where $\xi_m = 6.5$. The mean DM mass density within R is $\bar{\rho} = \rho_0/5.65$. Taking $a/c \sim 1/\sqrt{5}$ and $M/M_\odot = 10^9$ as an example, we would have $\rho_0 \sim 0.1$ g cm^{-3} and $R \sim 3 \times 10^9$ km. If we take $a/c = 0.1$ and $M/M_\odot = 10^{12}$ as another example, it follows that $\rho_0 \sim 10^{-11}$ g cm^{-3} and $R \sim 6 \times 10^{13}$ km (the present average mass density in the Universe is $\sim 4.5 \times 10^{-31}$g cm^{-3}). When disturbed, such critical DM halos would be vulnerable to gravitational contractions or collapses to form DMBHs. The collapsing phase of such a DM halo may involve a self-similar dynamic evolution [1]. For smaller a/c, the ρ_0 would be reduced rapidly and the DM halo radius R would become much larger than the eventual DMBH radius r_s.

By current observational inferences, the overall mass fraction of DM is $5 \sim 6$ times that of normal matter in the Universe. It would not be surprising that DMBHs could well exceed SMBHs and HMBHs by number and by mass. Such dynamic formation processes for DMBHs in a wide mass range can happen anywhere in the Universe whenever favorable conditions are available in DM halos or reservoirs because spherical dynamic collapse is sufficiently rapid. In particular, very massive DMBHs may also emerge in the early Universe in view of the fact that the mass content is dominated by DM on the whole in the Universe.

It is also possible to have mixed matter BHs (MMBHs) formed by accreting DM and normal matter together or in sequence [42]. All having the same gravitation property, DMBHs, MMBHs and normal matter BHs cannot be distinguished at this stage and it is possible that they are dormant by considerable numbers in the Universe including the early Universe. They can all be detected by gravitational lensing effects, by their mutual dynamic interactions with the surrounding normal matter and electromagnetic radiation produced therewith, and by gravitational wave emissions due to violent massive motions associated with inevitable 3D turbulences during dynamic collapses as well as due to merging. When magnetized fully or partially ionized gas medium is involved in dynamically forming DMBHs or MMBHs, 3D MHD turbulence can be sustained during the phase of dynamic collapses. Gas heating and acceleration of energetic charged particles are natural consequences in an environment of MHD turbulence. UHECRs may well also be created in such processes in association with BH dynamic formation. In certain situations when electromagnetic radiation from such magnetized gas medium is not easily detected, we may then have the impression that UHECRs reach us from nowhere in deep space [43].

Are there any tantalizing observational evidence for DMBHs and/or MMBHs? We venture to suspect that the SMBH of CID-947 ($M_{\rm BH} = 6.9^{+0.8}_{-1.2} \times 10^9 M_\odot$ [28]) and the HMBH of NGC 1277

($M_{\rm BH} = 1.7 \times 10^{10} M_\odot$ [29]) with their unusually high BH mass ratios to their respective host stellar mass might be candidates of DMBHs and/or MMBHs. In other words, the SMBH of quasar CID-947 and the HMBH of the compact lenticular NGC 1277 might have accumulated considerable amounts of DM during their respective dynamic collapse phases.

In relative isolation, such SMBHs, HMBHs, MMBHs and DMBHs may be detected by gravitational lensing effects under favorable conditions in principle. Such BHs in processes of turbulent dynamic formation and in close binary for various possible combinations as well as during their rapid merging can release inferrable or detectable gravitational waves [4, 5, 6, 44]. When SMBHs, HMBHs, MMBHs and DMBHs dynamically interact with their normal matter surroundings, they can be inferred or detected by commonly adopted methods as appropriate.

7. Neutral hydrogen environments of quasars near and far

We have detected numerous SMBHs and a couple of HMBHs in quasars near and far [26, 30, 31] − the farthest one with high redshift $z = 7.085$. The most massive quasar is close to $\lesssim 10^{11} M_\odot$ at $z \gtrsim 2$. The most luminous one for $z \gtrsim 6$ has the bolometric luminosity of $L_{bol} = 1.62 \times 10^{48}$ erg s^{-1}. The essence of various methods for observationally inferring SMBHs in quasars is the same with likely systematic errors by a factor of several, unless something is missed completely. The disk accretion scenario faces the unsurmountable challenge to remove disk angular momentum effectively even for nearby SMBHs and HMBHs. By the very nature of a BH, we do need electromagnetic radiations resulting from ambient dynamic interactions such as an accretion disk or activities to detect its presence and estimate its mass. Nevertheless, the present-day disk association with a BH does not necessarily mean that the entire mass acquisition of such a BH is completely from a surrounding accretion disk. The initial spatial distribution of angular momentum in a massive halo can have various possible forms. During gravitational collapses, those materials without angular momentum will fall in more directly and other materials with angular momentum may reduce size with faster rotation speed. In fact, morphologies of galaxies around $z \sim 3$ are rich in varieties and do not appear disk-like at all. In short, the key issue here is whether the formation of a BH is entirely due to a sustained disk accretion in all its lifetime or an accretion disk may be acquired simultaneously or later and mainly serves a valuable diagnostics for the BH presence.

Observationally, it would be natural to first explore relatively nearby quasar environments of SMBHs and HMBHs. The presence of several characteristic spectral lines and their line profiles offer basic ingredient information of detectable interstellar medium (ISM). The main challenge is that the central AGN or quasar is so luminous to overwhelm the surrounding ISM. Farther away from central activities with less intensive radiation fields, there may still exist considerable amount of neutral hydrogen gas. It would be of considerable astrophysical and cosmological interests to study neutral hydrogen 21cm lines from massive host halos and/or galaxies of quasars. As evidenced by nearby galaxies, one would expect higher concentrations of neutral hydrogen in halos and/or galactic outskirts of quasars than the average HI concentration in the cosmological space.

In reference to the prospect of searching high-z HI 21 cm emissions in the background Universe, a sensible strategy is to explore possible HI 21 cm emissions from host environment of quasars with increasing redshifts. This would offer a valuable evolutionary view with step-by-step calibrations. With the advent of the Square Kilometer Array (SKA) in the coming decade with unprecedented high sensitivity and high spatial resolution, it would be worthwhile to pursue this line of research.

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