ORIGIN AND EVOLUTION OF MASSIVE BLACK HOLES IN GALACTIC NUCLEI

R. D. Blandford
130-33 Caltech
Pasadena CA 91125 USA

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Abstract

Beyond all reasonable doubt, black holes are commonly found in the nuclei of most normal galaxies. In recent years, dynamical measurements of hole masses have transformed the study of their functioning and evolution. In particular, relating their masses, as measured contemporaneously, to the properties of distant quasars can constrain models of the combined evolution of black holes and their host galaxies. It is suggested that black hole growth is radiation-dominated and demand-limited with an e-folding time of ~ 40 Myr and that most local black hole mass was assembled in AGN with redshifts, $z > 2$, whose counterparts are not directly observed today. Black hole binaries have additional features and observable consequences.

1 INTRODUCTION

The central problem of developmental biology (for those who are not developmental biologists) is "Which came first, the chicken or the egg?". Likewise a central question for many of us who do not work regularly on galaxy formation is "Which came first, quasars or stars?". One reason why this is important is that a single proton, accreting on to a black hole, can spawn over a million ultraviolet photons which can ionize up to a million hydrogen atoms. This heating, in turn, controls the scale and the timing of the collapse of positive density gas fluctuations in the expanding universe and, ultimately, the formation of the earliest galaxies.

Now the traditional approach to galaxy formation has been largely deductive, working forward in time from the linear fluctuation spectrum. It is not clear how far this approach can be usefully followed in view of the great complexity of the physical processes involved, and our lack of understanding of which factors are most important. By contrast, I believe that it is now more productive to work, inductively, from direct observational data. This introduces several, fresh ingredients, including one that is of great concern at this meeting, namely that most large galaxies contain surprisingly massive black holes in their nuclei. This has direct dynamical implications for the central stellar distribution. Furthermore, although nuclear activity has hitherto been regarded as a sideshow, it now seems distinctly possible that the formation of a black hole is linked to the early evolution of its surrounding galaxy and may provide a crucial feedback for limiting star formation, for arresting its own growth, for moulding the morphology of the galaxy, for inducing or inhibiting collapse of further density perturbations in the neighborhood and for ionizing the intergalactic medium. For all of these reasons, it is very important to understand the role of black holes in galaxy formation.

The hypothesis that active galactic nuclei (including quasars) are powered by accretion onto massive black holes has been around since 1964 and has the immediate implication that most local galaxies should contain dormant, massive black holes. (See *eg* Krolik 1998 for a discussion of the circumstantial evidence for black holes in active galactic nuclei that has accumulated over the past thirty years.) We now know that, beyond all reasonable doubt, local galactic nuclei contain black holes with masses in the range $\sim 10^6$ - 3×10^9 $M_\odot$. Over thirty examples have had their masses measured dynamically using a variety of techniques and with varying degrees of confidence, (*eg* Richstone *et al* 1998). This has transformed the study of AGN as we now can make quantitative the relevant scales of length, time, power etc. Three of the most precise are NGC 4258 (3.6×10^7 $M_\odot$, Miyoshi *et al* 1995), our Galactic center (2.6×10^6 $M_\odot$, Genzel & Eckart 1997) and M87 (3×10^9 $M_\odot$ Macchetto *et al* 1997). It appears that most nearby, normal galactic nuclei contain massive holes. Even more remarkable is the development of the capability to measure the spin angular frequencies of black holes through the Fe line profiles (Tanaka *et al* 1995).

Let us now make some convenient definitions. Given a black hole mass,

M, accretion rate $\dot{M}$ and bolometric luminosity L, we can derive the equivalent length, time and energy

$$m \equiv 1.5 \times 10^{11} M_6 \text{cm} \equiv 5 M_6 \text{s} \equiv 2 \times 10^{60} M_6 \text{erg} \tag{1}$$

where $M_6 = (M/10^6 \mathrm{M}_\odot)$. We can also define the fiducial Eddington luminosity, accretion rate and timescale

$$\begin{aligned} L_{\text{Edd}} &= \frac{4\pi G M m_p c}{\sigma_T} \sim 3 \times 10^{10} M_6 \mathrm{L}_\odot \\ \dot{M}_{\text{Edd}} &= L_{\text{Edd}}/c^2 \sim 10^{23} M_6 \text{g s}^{-1} \\ t_{\text{Edd}} &= M/\dot{M}_{\text{Edd}} \sim 0.4 \text{Gyr} \end{aligned} \tag{2}$$

We also define $\dot{m} = \dot{M}/\dot{M}_{\text{Edd}}$, and $\epsilon = L/\dot{M}c^2$.

For illustration purposes, I shall adopt a Friedmann universe with $h \sim 0.6$, $\Omega_0 \sim 0.3$, $\Omega_\Lambda = 0$, with a total current density $\rho_0 \sim 3 \times 10^{10}$ $\mathrm{M}_\odot$ Mpc^{-3}, of which $\sim 3 \times 10^9$ $\mathrm{M}_\odot$ Mpc^{-3} is baryonic. The age of the universe at $z = 5, 3, 2, 1, 0$ is $t \sim 1, 2, 3, 7, 14$ Gyr, respectively.

2 ACCRETION

It has commonly been supposed that accretion proceeds through a thin disk with a radiative efficiency given roughly by the binding energy of the smallest, stable circular orbit, $0.06 - 0.42c^2$, dependent upon the spin of the hole. In this case, we expect that$\epsilon \sim 0.1$ and ($L \sim 10^{43} \dot{m} M_6$ erg s^{-1}, where $\dot{m} \equiv M/\dot{M}_{\text{Edd}}$. However, many observed objects are remarkable for being underluminous relative to the estimated gas supply. The case is best made for our Galactic center, where the supply of gas may be as high as $\sim 10^{22}$ g s^{-1} while the bolometric luminosity may be as low as $\sim 10^{36}$ erg s^{-1}. The efficiency of conversion of mass into radiant energy may then be as small as $\sim 10^{-7}c^2$, and is unlikely to be larger than $\sim 10^{-4}c^2$, three to six orders of magnitude below the conventional value. Similar claims can be made for other galaxies with measured hole masses.

Observations like these stimulated the development of Advection-Dominated Accretion Flow (ADAF) solutions for mass accretion rates well below the Eddington-value, typically $\dot{m} < \alpha^2$, where α is the viscosity parameter, (eg Kato *et al* 1998 and references therein). It is supposed that there is an efficient viscous torque and that energy is dissipated into the ions which only heat the electrons through Coulomb scattering so that the gas flow is essentially adiabatic (though not isentropic). This generally requires that $\dot{m} < \alpha^2$, where α is the viscosity parameter. The e-folding time for dormant black holes is then $> \alpha^{-2} t_{\rm Edd}$. Models of the spectrum formed by the hot gas in these flows can be adjusted to fit the observations of a wide variety of "underfed" black hole systems in impressive detail.

Despite this success, there are several concerns about the ADAF models. The most fundamental, dynamical worry is that the flows themselves have positive Bernoulli constant. This means that exposed gas has enough energy to escape to infinity. The fundamental reason why this happens is that viscous torque inevitably transports energy, as well as angular momentum, from small to large radius. An equally important concern about the radiative model is the assumption that the electrons adopt a relativistic Maxwellian distribution and avoid non-thermal particle acceleration, despite the fact that the flows become mildly relativistic, develop high Mach numbers and rely upon strong, magnetic dissipation to proceed. A relatively small admixture of suprathermal relativistic electrons will greatly increase the emitted flux.

For these, and other, reasons, a generalisation of the ADAF models - the ADiabatic Inflow-Outflow Solutions (ADIOS) have been developed (Blandford & Begelman 1998, 1999 in preparation). These drop the assumption of conservative mass flow and invoke a powerful wind which carries off mass, angular momentum and energy, enabling the remaining gas to accrete in a bound disk with negative Bernoulli constant. This applies when the hole is *underfed* relative to the Eddington rate. In the limiting case, the disk accretion rate at radius r increases, $\dot{M} \propto r$, between the horizon of the hole and a transition radius, $r_{\rm trans}$, within which the gas is supposed to be unable to cool. In some cases, *eg* the Galactic center, $r_{\rm trans} \sim 10^5 m$ and so it is possible for one proton at $r \sim m$ to sacrifice itself, altruistically, so that 10^5 of its fellow protons may escape to freedom. More relevantly, the gas density in the vicinity of the hole can be orders of magnitude smaller than in the ADAF models and the constraints on the emission correspondingly relaxed. Of course, real accretion does not have to correspond to this extreme case and rate at which any outflow carries off mass, energy and angular momentum can be freely assigned. Not surprisingly, observed spectra can also be fit with ADIOS solutions (Quataert & Narayan 1998). We must await high dynamic range 3D numerical hydromagnetic simulations (Balbus & Hawley

1998) to make more progress. What is important for our purposes is that in ADIOS models there is a distinction between the rate of mass supply and the rate of mass accretion and the radiative efficiency with respect to the rate of accretion need not be low. This means that the black hole mass is quite unlikely to grow during ADIOS accretion.

Similar considerations apply when the accretion is so rapid and the gas flows so fast that the radiation is trapped. Specifically when $\dot{m} > 1/\epsilon$, the radiation is advected out to a radius $r_{\rm trap} \sim \dot{m}m$. The flow will be radiation-dominated with $\gamma = 4/3$. Again, there are ADAF-like solutions (*eg* Begelman & Meier 1982) where the radiative efficiency is low and black holes can grow rapidly in mass relative to their radiated energies. However, these solutions are subject to the same dynamical objections as the ADAF solutions and it is likely that the accretion rate will again be self-limiting, independent of the rate of mass supply. What this implies, in practice, is that when the black hole is *overfed* with gas, it, will radiate at the Eddington limit and grow with an e-folding timescale $\epsilon t_E \sim 40$ Myr.

There is some observational evidence that this is occuring. SS433 and the Galactic superluminal sources appear to have supercritical outflows. Broad absorption line quasars comprise roughly ten percent of radio-quiet quasars and exhibit fast powerful winds that are probably accelerated to their terminal velocities by emission line radiation pressure. (It is widely believed, though not proven, that all radio-quiet quasars have these flows and that we only observe them when we lie in the equatorial plane.) However, it is not yet possible to relate the outflow rates to the hole masses and inflow rates.

For the intermediate, radiative case, $\alpha^2 < \dot{m} < \epsilon^{-1}$, there is probably not much mass loss. Traditional, disk accretion ought to be appropriate. The hole grows with an e-folding time $\sim t_{\rm Edd}/\dot{m}$.

3 MASS AND ENERGY

Consider, first, the local universe. The galaxy luminosity density is $\mathcal{L}_B \sim 10^8$ $L_\odot$ Mpc^{-3} (*eg* Binney & Merrifield 1998). As the fiducial luminosity $L_B^* \sim 3 \times 10^{10} L_\odot$, the bright galaxy density is estimated by $n_G \sim \mathcal{L}/L_B^* \sim 3 \times 10^{-3}$ Mpc^{-3}. If we adopt a mean stellar mass to light ratio of $(M/L)_B = 6$ in solar units and assume that most baryons in galaxies are associated with luminous stars, then the galaxy baryon mass density is $\sim 6 \times 10^8$ $M_\odot$ Mpc^{-3}.

Of this, individual bulge fractions range from ~ 0.1 for Scs to unity, for ellipticals, giving an average bulge mass density of $\sim 3 \times 10^8$ M$_\odot$ Mpc^{-3}. Most of the mass associated with galaxies is believed to be dark and non-baryonic. This is very hard to measure (and almost as hard to define), but a good guess, consistent with numerical simulations, puts the mean mass density as $\sim 10^{10}$ M$_\odot$ Mpc^{-3}, roughly 30 percent of the total mass density.

Turning to the measured black hole masses. (*eg* Richstone *et al* 1998). It has been argued that there is a correlation of the black hole mass, M_h with the bulge mass, estimated photometrically, M_B, (Magorrian *et al* 1998). $M_h = 0.006 M_B$ although the scatter is large. (Note, also, an intriguing correlation of M with the radio luminosity reported by Franceschini *et al* 1998.) The local hole mass density is then usually computed from the bulge luminosity density and is found to be

$$\rho_h \sim 2 \times 10^6 \mathrm{M}_\odot \mathrm{Mpc}^{-3} \tag{3}$$

(Note that this estimate is $\propto h^3$.)

We now have a better understanding of the evolution of bright galaxies. The earliest galaxies that have been found have $z \sim 5.5$ (*eg* Spinrad *et al* 1998), and are observed at an epoch when the universe was ~ 1 Gyr old. It is hard to quantify their density, but they cannot be too rare, based upon the manner by which they were discovered. By the time the universe is ~ 2 Gyr old ($z \sim 3$), the density of bright, $\sim L^*$, galaxies appears to be comparable with their contemporary density, n_G, although uncertainties in the reddening make these estimates difficult. We do not have good, direct measurements of the galaxy luminosity function at $t \sim 3$ Gyr, ($z \sim 2$), but can measure a small apparent dimming by a factor ~ 3 in L_B^*, from $t \sim 7$ Gyr, ($z \sim 1$), to the present, consistent with passive stellar evolution following the main star formation epoch and little change in the number of bright galaxies. However, there is a marked decrease in the density of low luminosity galaxies which outnumber the bright galaxies by a factor ~ 30 on the sky. We do not have a good understanding of the ages and fate of these faint galaxies, though plausible theories abound. The star formation rate, which is related to the rate of change of the luminosity function, appears to increase slowly to a value $\sim 10^8$M$_\odot$ Gyr^{-1} Mpc^{-3}, when the universe was ~ 4 Gyr old, ($z \sim 1.5$), and decline by roughly a factor thirty to the present day.

Turning next to quasars, the redshift 5 barrier has, also, been broken (Gunn, private communication) and new surveys promise an excellent harvest with $z > 4$. It appears that quasar evolution precedes and perhaps exaggerates that of galaxies with a slow increase in the quasar luminosity to its peak around $t \sim 3$ Gyr, ($z \sim 2$), followed by an *apparent* dimming $\propto t^{-3}$. At the epoch of peak quasar activity, $t \sim 3$ Gyr, a fraction ~ 0.003 of bright galaxies is a quasar at any time $n_Q \sim 10^{-5}$ Mpc^{-3}. Therefore, if every bright galaxy had a single quasar phase then this would last ~ 10 Myr.

It has long been recognised that local black hole masses can provide a quantitative link to past quasar activity (*eg* Lynden-Bell 1969). Following Soltan (1982), the comoving energy density of emitted quasar light is given by

$$U_Q = \frac{1}{c} \int dN_Q S(1+z) \tag{4}$$

where S is the observed flux and the integral is over all quasars on the sky. From the quasar counts, it is apparent that the integral is just starting to converge at $B = 22$ (or $\nu S_\nu = 5 \times 10^{-14}$ erg cm^{-2} s^{-1}), where the number increases at a rate of just under 2.5 per magnitude. The median redshift of these quasars is $z \sim 2$. As $N(B < 22, z < 2.2) \sim 70$ per square degree (Zitelli *et al* 1992), we estimate $U_Q(B) = 6 \times 10^{-18}$ erg cm$^{-3} \equiv 100$ M$_\odot$ Mpc^{-3}. This, of course, only refers to the light observed in the B band and emitted at ~ 1500Å. For this reason, we must apply a bolometric correction to convert it to the bolometric quasar energy density. This has been variously estimated (on quite insecure grounds) to lie in the range 10-30. If we choose a value of 20, and allow for 50 percent more higher redshift quasars, we obtain, $U_Q \sim$ 3000 M$_\odot$ Mpc^{-3}, in agreement with Soltan (1982) and Small & Blandford (1992), but a factor 3-6 smaller than obtained by Chokshi & Turner (1992). (The difference appears to be due to the inclusion of fainter quasars that are not directly counted.) Now, if the black hole mass density is built up during the quasar phase by accretion we can combine Eq. (3), (4) to deduce that the average radiative efficiency is $\epsilon \sim 0.01$, an order of magnitude smaller than anticipated, even assuming the Chokshi-Turner value for the radiation energy density. This argument has led many authors to deduce that quasars grow while accreting ineffciently.

There is a further way by which we might be underestimating U_Q. Fabian and Iwasawa (1999, and references therein), have proposed that the X-ray background comprise the combined emission from many AGN and that its distinctive, hard spectrum, below ~ 40 keV may be due to strong absorption. This hypothesis implies that much of the $\sim 10 - 100\mu$ infrared background, (estimated to be $\sim 10^5$ $M_\odot$ Mpc^{-3}, Hauser *et al* 1998), be re-radiated ultraviolet and soft X-ray emission produced by accretion onto black holes, thereby raising U_Q by up to an order of magnitude. One concern about this proposal is that most of the sources that make up the background must be low redshift AGN rather than more powerful objects at at high redshift, like the quasars, as we may have expected. This is simply because there is unlikely to be much photoelectric absorption above ~ 30 keV in the rest frame of the emitting galaxy, (equivalent to ~ 10 keV observed for $z \sim 2$) and so, in order to match the break in the background spectrum, it is necessary that the source redshifts be small. Alternatively, if the break is associated with the commonly-observed Compton cut-off energy in Seyfert galaxy spectra, which is $\sim 100 - 200$ keV, then redshifts $2 < z < 4$ are indicated. (The underlying spectra, below the cut-off energy, would have to be harder than those associated with local Seyferts, though.)

The Soltan argument may be illusory, because we probably do not observe directly the progenitors of the holes that dominate ρ_h. To clarify this point, observe that the bolometric luminosty of a $B \sim 22$, $z \sim 2$ quasar is $\sim 10^{13}$ $L_\odot$ (continuing to adopt a bolometric correction of ~ 20). This is the Eddington limit for a $\sim 3 \times 10^8$ $M_\odot$ hole. If we also adopt an efficiency $\epsilon \sim 0.1$, then it takes ~ 0.1 Gyr for an accreting quasar to increase its mass by a factor ~ 10. suggesting that quasars are active for $\sim 1/30$ of the time at $t \sim 3$ Gyr. Now there are $\sim 3 \times 10^6$ quasars observed, occupying $\sim 3 \times 10^{11}$ Mpc^3 of comoving volume at $z \sim 2$. Allowing for 30 times as many inactive holes, we estimate that the density of 3×10^8 $M_\odot$ holes at $z \sim 2$ is roughly ten percent of the density of bright galaxies. This is broadly consistent with the observed, local distribution of black hole mass, specifically, including most of the massive ellipticals and S0 galaxies. Note that less massive holes, with $M < 3 \times 10^7$ $M_\odot$, are likely to be too faint to have been detected as quasars at $z \sim 2$. but might have been the unresolved, nuclei of active galaxies at $z \sim 3$. Indeed most of the growth of lower mass black holes could have been rendered invisible by the presence of stellar light. There is plenty of time to allow black holes to grow from quite small masses with e-folding timescales ~ 40 Myr. A more formal treatment, repeating the analysis of Small & Blandford 1992, will be presented elsewhere.

4 FORMATION AND EVOLUTION

Having suggested an empirical relationship between black holes and their host galaxies, it is natural to speculate upon how this may have come about. Under the hierarchical model of galaxy formation, small structures form first and agglomerate into larger structures. Above the Jeans' mass, bound mass perturbations will virialize and shock and then collapse at a rate controlled by the rate of cooling and, eventually, the rate of outward transport of angular momentum (*eg* Haiman & Loeb 1998). The former is controlled at early times by the subtle chemistry of molecular hydrogen and at later times by atomic and ionic line cooling. The latter is probably dictated initially by gravitational torques associated with departures from axisymmetry and, ultimately, by magnetic field. Star formation and merging with neighboring protogalaxies occurs simultaneously with collapse and the competition between these various processes will probably only be understood properly from observations.

One scenario (Silk & Rees 1998, Haehnelt *et al* 1998), is that a $\sim 10^6$ $M_\odot$ black hole forms by coherent collapse in the nucleus before most of the bulge gas turns into stars. The black hole accretes and radiates at the Eddington limit, driving a wind with kinetic luminosity ~ 0.1 of the radiative luminosity. This deposits energy into the bulge gas, and will unbind it on a dynamical timescale if $0.1L_{\rm Edd} > \sigma^5/G$, where σ is the bulge velocity dispersion. This implies that the black hole mass will be limited to a value where it is able to shut off its own fuel supply

$$M < 10^5 \left(\frac{\sigma}{100\mathrm{kms}^{-1}}\right)^{5/3} \mathrm{M}_\odot. \tag{5}$$

(If it is further assumed that all bulges form dynamically at the same time, the $\sigma \propto M_{\rm bulge}^{1/3} t^{1/3}$ and $M \sim M_{\rm bulge}^{5/3}$, instead of the linear relation proposed above.)

There are many issues that are unaddressed by this model, including the efficiency of star formation, the transport of angular momentum and radiative cooling. Furthermore, it is quantitatively inaccurate. because Eq. 5 does not appear to be satisfied. (*eg* σ(M87)= 330 km s^{-1} $= 2.5\sigma$(Galaxy),). Nonetheless, it does provide a good example of a qualitative mechanism whereby the galaxy can limit its own black hole mass.

Indeed, in a radical extension of this idea, a bright AGN may also limit infall of gas to form a disk, though Compton heating, radiation pressure on dust or direct interaction with a powerful wind. When the hole mass and luminosity are large, the weakly bound, infalling gas will be blown away and an elliptical galaxy will be left behind. Only when the hole mass is small, will a prominent disk develop. In this case, the bulge to disk ratio, (or equivalently the Hubble type), should correlate with the hole mass fraction. It would be interesting to perform some numerical hydrodynamical simulations that included dynamical energy input asssociated with an AGN. The recent report by McClure *et al* (1999 in press) that essentially all quasars are associated with elliptical galaxies is in support of this idea.

The black hole mass may also be limited dynamically. Sellwood & Moore (1999) have suggested that strong bars inevitably form in the centers of nascent galaxies and channel mass inwards to the growing central black hole until its mass is ~ 0.02 of the mass of the disk. At this point, the bar weakens and infalling mass forms a much more massive bulge which, in turn, suppresses re-formation of a bar through the creation of an inner Lindblad resonance. By contrast, Merritt (1998) has suggested that the central hole may make the central stellar orbits become chaotic, with the consequence that non-axisymmetric disturbances are smoothed out and the rate of infall of accreting gas falls. These are quite distinct, and no less plausible, mechanisms by which a black hole can determine galaxy morphology.

In summary, it seems entirely possible that black holes form first at quite large redshifts, $z >> 2$ and can grow to their present sizes with standard radiative efficiency, by the time of the main quasar epoch at $t \sim 3$ Gyr. There are several, plausible mechanisms for switching off the growth of the hole, some of which have observable signatures.

5 BLACK HOLE BINARIES

It is apparent that many high mass galaxies have undergone major mergers and, as both partners are likely to contain massive black holes, it is almost inevitable that merging black hole should be quite common. The route to coalescence has been well explored (eg Begelman, Blandford & Rees 1982, Quinlan & Hernquist 1997). A captured black hole with mass in excess of $\sim 10^6$ M$_\odot$ can be dragged into the galactic nucleus of the larger, capturing galaxy by dynamical friction. Eventually the binary will harden when the interior mass is dominated by the host hole and the orbital speed exceeds the central velocity dispersion. The evolution will continue by ejecting low angular momentum stars until the holes are sufficiently close for the radiation of gravitational waves to dominate the evolution.

There are several possible and potentially observable implications of these mergers. Firstly, the dissipative formation of gas-rich galactic nuclei may well account for the cuspy, power-law central density distributions, with "disky" isophotes and substantial rotation, associated with low luminosity ellipticals and spiral bulges (*eg* Faber *et al* 1997). If major merger subsequently occurs and two massive black holes with their stellar entourages merge, in an essentially dissipationless manner, this may create the "cores" associated with many massive ellipticals. Secondly, this fits in well with the notion that the giant radio sources are powered ultimately by black hole spin which may be re-established in major merger events (Wilson & Colbert 1995). Thirdly, it is just possible that we catch find a rare spectroscopic binary black hole, most plausibly in a low mass, local Seyfert galaxy (*cf* Gaskell 1996). Fourthly, the actual coalescences, may be detectable in the future from the gravitational radiation pulses that they produce through missions like LISA (Bender, these proceedings).

6 CONCLUSION

This is a time of rapid progress in understanding the relationship of black holes to their hosts. We are starting to piece together a description, initially qualitative, but now, increasingly quantitative, of how, where and when the massive black holes were formed. However, the most intriguing question of all is the one with which I began. Where were the first ionising photons emitted (*eg* Madau 1999)? Was it from a population of high mass stars which stimulated cooling and collapse or did galaxies form from the inside out, growing their nuclear black holes before their stars formed? We may have to await the next generation of space-borne infrared and submillimeter telescopes before we are confident of the answer.

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