QSO's from Galaxy Collisions with Naked Black Holes

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In the now well established conventional view (see **Rees** [1] and references therein), quasi-stellar objects (**QSOs**) and related active galactic nuclei (**AGN**) phenomena are explained as the result of accretion of plasma onto giant black holes which are postulated to form via gravitational collapse of the high density regions in the centers of massive host galaxies. This model is supported by a wide variety of indirect evidence and seems quite likely to apply at least to some observed **AGN** phenomena. However, one surprising set of new Hubble Space Telescope (**HST**) observations [2-4] directly challenges the conventional model, and the well known evolution of the **QSO** population raises some additional, though not widely recognized, difficulties. We propose here an alternative possibility: the Universe contains a substantial independent population of super-massive black holes, and **QSO**'s are a phenomenon that occurs due to their collisions with galaxies or gas clouds in the intergalactic medium (**IGM**). This hypothesis would naturally explain why the **QSO** population declines very rapidly towards low redshift, as well as the new **HST** data.

The recent direct observation which calls the traditional model into question is the result of attempts to image the host galaxies of low redshift QSO's using HST. So far, 20 such systems have been imaged deeply with WFPC2 (Bahcall, Kirhakos & Schneider [2-4]). A few of the images show the expected normal, giant galaxy with the QSO shining from its nucleus; however, the remainder show a somewhat bewildering array of different

local environments for the QSO activity: in some cases the QSO is positioned somewhere in the midst of what appears to be a system of galaxies in collision but not associated with any obvious galaxy nucleus. In many cases, there are a few dwarf galaxies within several kpc of the QSO but none detectable (to limits well below L^*) directly associated with it. There are even cases in which the QSO seems to have no particular association with any visible galaxy, aside from being a part of some possible loose galaxy group. In any case, the data clearly demonstrate that a major fraction of at least low redshift QSO's do not conform to the most straightforward predictions of the conventional scenario.

The difficulties for the standard scenario raised by observed QSO population evolution (see Ref. [5]) are neither so direct nor so clearly recognized, but they may also represent important clues. There are in fact three such puzzles. The first is that at $z > 4$, when the Universe was less than 10% of its present age (for $\Omega_o = 1$), the most distant QSO's we have so far located were as luminous and roughly as numerous as those present at any later epoch and far brighter and more common than they are at the present epoch [6,7]. Moreover, this population of objects may well be present at even higher redshifts; they are difficult to locate not because they are faint (some $z > 4$ QSO's are brighter than 18th magnitude!) but because the comoving volume per redshift interval is decreasing or increasing less rapidly than at low redshift (depending on the cosmological model) and the QSO light is rapidly shifting into the near IR. The second problem for the conventional model is to explain why the giant black hole remnants of the QSO's which were so luminous at $z \sim 2$ are so dark and inactive at the present, despite the presence of a dense ISM and stellar population in the nuclei of many giant galaxies [8]. The third puzzle is the remarkably fast drop in the QSO population at redshifts below about 2; during this period the comoving emissivity of luminous QSO's drops by orders of magnitude and with a halving time substantially shorter than the concurrent cosmic expansion time scale [7].

It is useful to recall that the natural *a priori prediction* of the conventional model would

be quite different. Most structure formation scenarios (particularly in high Ω_o universes) predict that increasingly massive objects form at successively later epochs. Moreover, processes of gravitational collapse and accretion would be expected to accelerate and produce ever more massive and rapidly growing black holes, especially in the very high density environments at the cusps of the nuclei of bright galaxies. This would lead to the expectation of a QSO population becoming more luminous and numerous with time as structure formation and the nonlinear evolution of galactic nuclei proceed. Even if one postulates some limit to terminate the luminous QSO phase, such as exhaustion of the accretion fuel supply or inability to tidally disrupt passing stars [9], it is difficult to see why it should apply so synchronously as observed. Of course, given our inability to reliably predict the details of the complex, nonlinear evolution of galactic nuclei and black hole accretion processes, it has proven possible to *a posteriori* explain the QSO population evolution in various, sometimes *ad hoc*, ways [10-13].

Motivated by the Bahcall *et al.* [2-4] observations and these shortcomings of the conventional model we here investigate the alternative hypothesis that the Universe contains a substantial population of massive ($\sim 10^8 M_\odot$) black holes existing independently of any host galaxy and perhaps even formed by rather different physical mechanisms. QSOs are then identified with the accretion luminosity and other activity generated when one of these "naked" black holes collides with a galaxy or a massive IGM cloud. In addition to trying to account for the unexpected results of the HST study, it is expected that such a scenario will be able to naturally account for the large and extremely rapid decrease in QSO activity in the recent history of the Universe. Thus, although the postulated "naked" black hole population may seem rather *ad hoc*, it offers the possibility of understanding at least two otherwise quite puzzling observations.

This simple scenario raises a host of detailed theoretical considerations. These include the efficiency with which the black hole can accrete gaseous material from the galaxy or

cloud with which it is colliding (as a function of gas density, angular momentum, composition, ...), the required number density of the "naked" black holes (relative to available baryons and other limits), their formation mechanisms and epochs, possible effects on the cosmic radiation background (CRB) spectrum, gravitational lensing consequences, relation to those QSOs and AGN which do seem to reside in the nuclei of $L \sim L^*$ galaxies, possible explanations for QSO phenomenologies and classifications, and so forth. In this discussion, we consider a few of the more critical points briefly, but we do not claim to have resolved any of these theoretical issues conclusively. Rather, our main purpose is to suggest a new qualitative scenario for the nature of at least some QSO's and to show that it is not immediately excluded by any simple considerations.

The typical black hole mass of interest is $\sim 10^8 M_\odot$ at around $z \sim 2$. The characteristic luminosity is set by the Eddington limit, at which radiation pressure on free electrons balances gravitational forces:

$$L_E = 4\pi G M_h m_p / \sigma_T = 1.3 \times 10^{46} M_8 \text{erg s}^{-1} \tag{1}$$

where G is Newton's constant, M_h is black hole mass, m_p is proton mass, σ_T is the Thomson scattering cross section and M_8 is the black hole mass in units of $10^8 M_\odot$. This is a typical luminosity for bright QSOs. Accretion rates needed to maintain this luminosity are of order $2\epsilon_{0.1}^{-1} M_\odot \text{yr}^{-1}$, where $\epsilon_{0.1}$ is the fraction of the accreted material's rest energy which is emitted radiatively in units of 0.1. In particular, it is expected that a black hole moving with a characteristic velocity v through a diffuse medium of density n will produce an accretion luminosity [14,15]

$$L = 1.0 \times 10^{45} M_8^2 \epsilon_{0.1} (\frac{v}{100 \text{km/s}})^{-3} (\frac{n}{3 \text{cm}^{-3}}) \text{ergs/s}, \tag{2}$$

which is of order the luminosity of the low redshift QSO's observed by Bahcall *et al.*. Some combination of higher densities in the ambient medium, lower encounter velocities and/or

more massive black holes would be required to achieve 10^{46} erg/s luminosities characteristic of high redshift QSOs.

What cosmic density of black holes is required to produce the observed QSO population? Let us write the comoving number density of black holes as n_h, and that of galaxies as n_g. The encounter rate is then written

$$R = n_h n_g (1+z)^6 \sigma v, \tag{3}$$

where σ is the cross section such that an encounter gives a QSO and v the relative velocity. For an order-of-magnitude estimate, let us assume that 30% of baryons are captured in galaxies and 10% becomes black holes of mass $10^8 M_\odot$. We assume that masses of galaxies are distributed according to the Schechter luminosity function with $M_{\mathrm{baryon}}/L \sim 10$, and that the relative velocities of a galaxy and a black hole are typically 100km s^{-1}. We also assume that QSO activity takes place when black holes crosses the galaxy within its Holmberg radius (at a baryonic surface density $\approx 10 M_\odot$ pc^{-2}); we estimate the size of a galaxy to be $\sim 14 (M_B/10^{11} M_\odot)^{0.4}$ kpc. We take the slope of the Schechter function to be $\alpha = -1.5$ in agreement with the numerous dwarfs reported in several recent studies [16-18]. The integral over the Schechter function is dominated by objects with $10^8 - 10^{10} M_\odot$ of gaseous material.

We note that the mass of $10^8 M_\odot$ is close to the minimum mass needed for bright QSOs; a less massive galaxy would not supply sufficient fuel to sustain the QSO luminosity through a characteristic crossing time. A fuel reservoir of $10^9\ M_\odot$ could shine for about 10^9 years at the Eddington luminosity if $\epsilon_{0.1} = 1$. From (3) we find that the encounter rate $R \sim 4.0 \times 10^{-22} (1+z)^6 h^{-2}$ s^{-1} Mpc^{-3} or equivalently, $1.3 \times 10^{-4} (1+z)^6 h^{-3}$ Mpc^{-3} per inverse Hubble time, where h is Hubble's constant in units of 100 km^{-1} s^{-1} Mpc^{-1}. Thus, the cumulative number of collisions (which we identify as QSO outbursts) around $z \sim 2$ is about $0.018 h^{-3}$ Mpc^{-3} in physical density or $0.0007 h^{-3}$ Mpc^{-3} in comoving units. These

numbers are a conservative estimate, since in reality, we expect some correlation in the distribution of QSOs and galaxies which would significantly increase the rate of collisions. In addition, QSO activity might result from the collision of black holes with some of the denser clouds in the IGM, rather than with a galaxy, thus further increasing the collision rate or reducing the required black hole population.

We note that the total mass density of black holes that ever shone as QSOs can be estimated reliably from their cumulative observed flux [19]. A modern estimate is $n_h \sim 0.001 - 0.002 M_8^{-1}$ Mpc^{-3} [20], in comoving coordinates. The fact that this number density based on the observed QSO population agrees with that inferred above from the collision rate calculation, within the substantial uncertainties of the input parameters (including h) and our very simplified treatment, is encouraging. This density is about $0.1 h^{-3}$ that of luminous galaxies and is at least $\sim 10^2 h^{-3}$ times higher than the peak number density of QSOs, which already suggests that QSOs are made and fade one after another.

A particularly notable feature is the $(1+z)^6$ dependence of the encounter rate. Since we expect that the lifetime of $10^8 - 10^9 M_\odot$ QSOs is of the order of $0.6 - 6 \times 10^8$ yr, considerably shorter than the Hubble time, we predict that the number density of QSOs decreases as $(1+z)^6$ towards $z = 0$ in gross qualitative agreement with observations. Of course, since the other factors in equation (3) (n_g, σ, v) might evolve with redshift, the situation could be considerably more complex, but these effects will be dominated by the $(1+z)^6$ factor unless the evolution is extreme.

The Bahcall *et al.* observations [2-4] show that QSOs are occasionally associated with host galaxies, sometimes spirals and sometimes ellipticals. This does not necessarily contradict the basic model presented here. While most QSOs would lose their activity rather quickly, either due to the end of the collision or the exhaustion of fuel in low mass galaxies, close encounters with more massive galaxies will sometimes lead to capture of the

black hole via dynamical friction and produce much longer lived activity. The dynamical friction will eventually bring the black hole into the centre of a galaxy. The time scale for a $10^8 M_\odot$ black hole to spiral into the nucleus of a typical giant galaxy from an initial radius of ~ 10 kpc is of order 10^{10} yrs [21]. It is interesting to see that the nucleus of 3C273 is not at the centre, and there are a few other examples seen in the QSO sample of Bahcall *et al.* In a predictive sense, when the active nucleus is found at or near the centre of a galaxy, we would expect a massive, high density host galaxy capable of producing strong dynamical friction.

As for the formation of black holes, our suggestions are not more than speculative. According to standard hierarchical clustering models, small mass objects collapse earlier; typically one expects large numbers of bound objects of $\sim 10^5 - 10^7 M_\odot$ before $z \sim 10$. Alternatively, more unconventional structure formation models such as PBI [22] or cosmic textures [23] can produce very nonlinear structure formation on small mass scales at early epochs. Of course, the black hole formation mechanism might be quite unrelated to those that form galaxies and other familiar structures. It is also worth noting that early formation of a galaxy-independent population of massive black holes has been invoked and investigated in a variety of other astrophysical connections [15,24-28].

In any case, we may suppose that a small fraction of baryons go into black holes when Compton cooling is very efficient (i.e., $z > 10$), as a generalization of the Rees & Efstathiou scenario [9]. Some of such black holes may eventually grow to $10^8 M_\odot$ by $z = 3 - 4$. Let us assume that the initial black hole mass is M_{hi} formed at around $z \sim 10 - 20$. If a fraction f of the binding energy of the forming black holes is deposited into the CRB; then the amount of distortion to be observed as Zel'dovich-Sunyaev effect is $y_c = \delta\rho/4\rho_{\mathrm{CRB}}$, which must be smaller than the observed limit 2.5×10^{-5} [29]. This means that the initial mass of black hole be smaller than $\sim 10^5 M_\odot$ for $f = 0.1$. On the other hand, the characteristic accretion time is $t_E = 4 \times 10^8$, and the mass of a black hole can grow as fast

as $M_h(t) \sim \exp(t/\epsilon t_E)$ where ϵ is the radiative efficiency, usually assumed of the order of 0.1. Hence, the available time is enough for more than 20 e-folds, sufficient to bring the mass to $10^8 M_\odot$ well before $z \sim 4$, though the availability of an adequate accretion fuel supply is a nontrivial requirement [6]. This exponential increase of the hole mass, and hence accretion luminosity, would explain the rapid rise of a bright QSO population before $z = 3 - 4$ [30].

Gravitational lensing provides a potential direct method for detecting the postulated black hole population [31]. Unfortunately however, the angular splittings, roughly 0.01 arc sec, and per source probabilities of multiple imaging, less than 10^{-3} at $z = 2$, are so small as to preclude any useful tests of our hypothesis based on available data sets.

Our primary conclusions can then be stated as follows: The conventional and in many respects successful model for QSOs [1] is severely challenged by recent HST data and has difficulty accounting for their well established population evolution. The alternative scenario suggested above could better account for these observations and does not manifestly violate any other empirical constraints. Thus, it merits further exploration.

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