The Rise and Fall of the Quasars

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Abstract. The coherent rise and fall of the quasar population is discussed in terms of gas accretion onto massive black holes, governed by the hierarchically growing environment. The rise is related to plentiful accretion during the assemblage of the host galaxies; the fall to intermittent accretion when these interact with companions in a group. The LFs are computed out to \( z = 6 \), and are related to the mass distribution of relict BH found in local galaxies. The histories of the QS and of the star light are compared.

1. Evidence

The bright quasars exhibit remarkable permanence and remarkable variations: the spectra (including the optical emission lines) are basically similar for individual QSs shining at redshifts in the full range \( z \approx 0 - 5 \), throughout most of the universe life; meanwhile, the population undergoes substantial changes. These look well organized, as shown by surveys in the radio, the optical and the X-ray band (see Shaver et al. 1996, Osmer in this Volume, and references therein). In fact, the bright QS population rises and falls steeply, culminating at \( z \approx 3 \pm 0.5 \); fig. 1 represents this course in terms of optical light density, and compares it with the run of the star light density as given by Madau 1997.

Over the first few Gyrs of the universe life the number of bright QSs grows, and the luminosity functions mainly rise in normalization, a so-called negative density evolution. Instead, after \( z \approx 3 \) the optical LFs fall to nearly blend in with the local Seyfert 1 nuclei. Luminosity evolution apparently prevails, but some positive density evolution also occurs; in addition, the optical LFs flatten toward us to comprise more bright objects than previously recognized (La Franca & Cristiani 1997; Goldschmidt & Miller 1997; Köhler et al. 1997).

On the other hand, aimed images from HST and from the ground in optimal seeing conditions (Hutchings & Neff 1992, Disney et al. 1995, Hasinger et al. 1996, Bahcall et al. 1997) extend to quasars out to \( z \approx 0.3 \) the evidence of a complex environment nailed down by Rafanelli et al. 1995 for the local Seyferts. In fact, up to 1/2 of the hosts mapped are found to be either engaged in galaxy interactions and in merging events, or to have close neighbors, even submerged within the host body. At a somewhat wider range, the QS environments are found to comprise some 10 – 20 galaxies on average (Fisher et al. 1996), the membership of a group.

Thus the evidence points toward one basic engine, but with working regimes related to the surrounding structure. We shall discuss how such connection gives rise to non-monotonic evolution.
2. Paradigms

QSs as individual sources are held to be powered by gas accretion onto massive black holes. This had been widely argued to explain outputs up to $L \sim 10^{48}$ erg s$^{-1}$ with large $L/M$ and high apparent compactness, considering also the terminal stability of the BHs. The paradigm envisages extracting the power $L$ from a mass accretion $\dot{M}$, at distances $r$ down to a few times the Schwarzschild radius $r_S$ and with radiative efficiencies up to $\eta = L/c^2 \dot{M} \sim r_S/r \sim 0.1$.

Direct evidence confirming the paradigm is now mounting (see Rees 1997), while the need for high $\eta$ is weakening. This is because relict BHs – expected to reside in normal galaxies keeping the record of the mass accreted during their whole career – are now found with number $\times$ masses exceeding the expectations under top efficiency (Kormendy & Richstone 1995, Magorrian et al. 1997).

But the paradigm has little to say – directly – concerning the rise and fall of the QS population. In fact, accretion drawing from an unlimited mass supply but self-limited by the BH radiation pressure in the Eddington regime yields luminosities that scale like $L_E \simeq 10^{46} M_{BH}/10^8 M_\odot$ erg s$^{-1}$, and exponentiate on the short time scale $\eta t_E \simeq 4 \times 10^7$ yr, or last even less according to Haiman & Loeb 1997. Thus the activities of the individual QSs constitute just short flashes compared with the evolutionary times of a few Gyrs or with the population lifespan of $\sim 12$ Gyr. A complementary, coordinating agency is called for, to organize all those flashes into a coherent rise and fall over an Hubble time.

Here enters the other paradigm, the hierarchical growth of structures which builds up the BH environment and the gas reservoir, and regulates the accretion. The gas may be held at bay on scales $\gtrsim 10^2$ pc in an axisymmetric gravitational potential where the angular momentum $j$ is conserved. But such symmetry is broken during the host galaxy build up, when strongly asymmetric events of merging occur; these allow plentiful mass inflow. Subsequently, the hosts
stabilize but are enclosed in groups, where they interact with companion galaxies. The potential is again distorted giving rise to episodes of mass inflow, recurring but gradually petering out as groups are reshuffled into clusters.

We maintain, following up CPV97, that in both dynamical regimes $j$ at times is not conserved, providing a condition necessary for growing new BHs, or for refueling the old ones. The transitional mass from a large galaxy to a small group is around $5 \times 10^{12} M_\odot$; in the hierarchical cosmogonies this corresponds to $z \simeq 3 \pm 0.5$, depending on cosmogonical and cosmological details. In any case, such values interestingly fall in the range where the bright QSs peak.

3. Bimodal accretion

Hierarchical cosmogony (see Peebles 1993) envisages larger and larger structures condensing out of gravitationally unstable density perturbations dominated by dark matter. In the critical universe the typical dark halos condensing and virializing at the epoch $t$, so attaining density contrasts $\rho/\rho_u(z) \sim 2 \times 10^2$, scale up in mass after $M_c \propto t^{4/(n+3)}$; for cold DM perturbations $n$ slowly increases with $M$ in the range $\sim -2.5 \div -1.5$. The halo growth may be visualized as a sequence of merging events of unequal, sometimes comparable, blocks. Thus if a typical rich cluster forms now, a small group formed at $z \simeq 2.5$, and most galactic bulges formed before. But the actual condensed masses are widely dispersed around $M_c$; correspondingly, their number rises prior to $t_c \propto M^{(n+3)/4}$, but declines only slowly thereafter. Even in the adverse open cosmologies with $\Omega_o < 1$ a similar trend is retained until the perturbations freeze out at $1 + z \simeq 1/\Omega_o$.

A subgalactic building block of DM with $M \sim 10^{10} M_\odot$ allows a BH of nearly $10^6 M_\odot$ to form, involving a baryon fraction around $\epsilon \sim 10^{-4}$. The galaxy assemblage goes on by repeated, chaotic merging; the baryons lose angular momentum to the DM at a rate set by the number density of substructures surviving in the gas and in the DM, and so approximately proportional to $\rho_u(z)$. Inflow is plentiful and accretion only self-limited, to yield luminosities $L \sim L_E \propto M_{BH} \propto \epsilon M$ where $\epsilon$ may still vary with $M$ and $z$ as discussed below.

In groups, many simulations (see Governato, Tozzi & Cavaliere 1996) have shown galaxy interactions to be frequent and strong. This is due to the high density of galaxies $n_g \propto \rho_u(z)$ and to the low velocity dispersion $V \propto M^{1-n}/12$, still so close to the galaxian $v_g$ as to allow dynamical resonance (such conditions no longer hold in clusters). Nearly grazing encounters occur frequently on the time scale $\tau_r \sim 1/\pi v_g^2 n_g V$, and produce outright galaxy aggregations (Cavaliere & Menci 1997), cannibalism, or interactions strong enough to perturb the potential and cause $j \neq $ const again. Simulations of single, aimed interactions (see Barnes & Hernquist 1991) show in detail how a sizeable fraction of the gas in both partners loses $j$ and is driven toward the main galactic nucleus, down to a distance limited to now only by the computational dynamic range.

So the BH bimodal fueling during host formation and interactions is unified and coordinated by the hierarchical evolution of structures. This provides the necessary external condition for mass inflow, while ultimate acceptance by the BH is set by the radiation pressure. All that does not end the story, however.

Initially, with copious inflow the stability of any intermediate structure against energy deposition conceivably limits the BH to $M_{BH} \propto (1 + z)^{2.5} M^{5/3}$
(HNR97), corresponding to $\epsilon(M, z) \propto (1 + z)^{2.5} M^{2/3}$. At last, when external conditions allow only inflows $\dot{M} \lesssim 10^{-2} L_E/c^2$, one expects energy advection from the accretion disk down the BH horizon before the electrons share and radiate the ion energy. If so (but see Bisnovatyi-Kogan & Lovelace 1997), the residual emission should peak in radio and in hard X-rays (Di Matteo & Fabian 1997) and be low in the optical; weak AGNs at last would break the spectral permanence by their non-equilibrium condition. This is supported by various lines of evidence: optical activity at very low levels is detected in a sizeable fraction of normal galaxies (Ho, Filippenko & Sargent 1997); X-ray galaxies with narrow optical lines are being detected, weak but so numerous as to conceivably saturate the XRB at $\sim 10$ keV (see Hasinger 1997); these advective accretion flows with low $\eta$ may constitute a stealthy addition to the relict BH masses.

4. Population kinetics

Bimodal fueling of BHs is conveniently described in terms of two components of the LFs at any $L, z$:

$$N(L, z) = N_1(L, z) + N_2(L, z).$$

The component $N_1$ represents new BHs growing and flaring up during the host buildup, and dominates for $M < 5 \times 10^{12} M_\odot$ or for $z \gtrsim 3$ on average. Instead, $N_2$ represents BHs reactivated by interactions, and dominates in structures with $M > 5 \times 10^{12} M_\odot$ for $z \lesssim 3$, and especially in groups.

The computation of $N_1$ may be visualized in terms of the kinetic equation proposed by Cavaliere, Colafrancesco & Scaramella 1991, which (setting the free $f(M)$ from the integration so as to conserve the total condensed mass) generates the mass function $N(M, z)$ of Press & Schechter 1974:

$$\partial_t N = N/\tau_+ - N/\tau_- \quad \text{with} \quad \tau_- = 3t/2, \quad \tau_+ = \tau_-(M/M_c)^{-(n+3)/3}.$$  

The positive driving term describes the build up of new host halos on a time scale $t_g \sim t$. Their destruction on a similar time scale is described by the negative term. BHs masses and luminosities grow in the self-limited regime for $\Delta t \sim \eta t_E \lesssim t$ mainly by such merging events rather than by continuous accretion onto a standing BH. Then the LFs are obtained in the form $N_1(L, z) dL \propto (\Delta t/t) \rho_0^2(z) N(M, z) dM$.

A more complex story concerns the component $N_2$ (see fig. 2). This is driven on the time scale $\tau_r$ by the random reactivations of the $N_r$ dormant BHs, so the driving term for the kinetics is here $N_r/\tau_r$. Now the activity is supply-limited and mostly sub-Eddington (Cavaliere et al. 1988, Small & Blandford 1992). The BHs restart their bright career from a low luminosity $L_i$, and brighten up on the scale of the flyby time $2r_g/V \sim r_g/v_g \sim 2 \times 10^8$ yr, which is taken care of by the transport term $\partial_t (\dot{L} N_2)$ in the kinetics. They attain an average $L_b$, which sets the break in the LFs; statistically they quench off with increasing probability $\tau_+^{-1} \propto (L/L_b)^{\phi} r_g/v_g$ (with $\phi \sim 1$), and this sets the slope at the bright end. All that is expressed by the kinetic equation

$$\partial_t N_2 + \partial_L (\dot{L} N_2) = \delta(L - L_i) N_r/\tau_r - N_2/\tau_L.$$  

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To close the argument, the last term integrated over $L$ provides one input to the number $N_r$ of dormant BHs, the other coming from those still forming and flashing up as described by $N_1$; the component $N_2$ arises in groups from $N_1$ and requires no independent normalization. We normalize $N_1$ to the data at $z \simeq 4$. Adopting the stability limit $M_{\text{BH}} \propto (M/10^{13} M_\odot)^{2/3} M$ (specifically, we use the coefficient $10^{-3} [(1 + z)/5]^{2.5}$) has interesting virtues (HNR 1997): adequately flat LFs obtain at high-$z$; the number of QSs visible for $\Delta t \simeq 0.1 t_E$ is consistent with that of the high-$z$, star-forming galaxies (Steidel et al. 1996).

5. High and low-$z$ luminosity functions

Fig. 3a shows the LFs for $z \gtrsim 3$ computed in the critical universe using for the perturbations the tilted CDM spectrum normalized to COBE/DMR (see Bunn & White 1997); these are compared with optical data adopting the bolometric factor $\kappa = 10$. For such redshifts not enough groups have yet formed for $N_2$ to emerge to relevance; the evolution of $N_1$ looks like the negative DE type.

For $z \lesssim 3$, instead, $N_2$ emerges and dominates the evolution. But to actually compute it, we have to consider where the main gas reservoir resides. Fig. 3b represents the low-$z$ behavior when the accreted gas is provided mainly by the host reservoir (say, with a constant fraction used up in each interaction, also constituting the main gas sink); then $-\dot{M}_{\text{gas}}/M_{\text{gas}} \simeq \tau_r^{-1} \simeq -L_b/L_b$ holds. But in groups or clusters evolving hierarchically in the critical universe $\tau_r \propto t$ closely obtains, since $V \propto t$ obtains for $n \simeq -2$, while $n_g \propto \rho_u(z) \propto t^{-2}$ applies. The result is $L_b(t) \propto t^{-t/\tau_{\text{ro}}}$; with $\tau_{\text{ro}}$ around 6 Gyr, scaled to groups from the classic census of local interacting galaxies by Toomre 1977, this reads $L_b \propto (1 + z)^3$.

This implies LE dominant for $z < 3$, with LFs flattened at the faint end by the brightening over the flyby time, $N(L) \rightarrow L^{-1-t/\tau_r(t)}$. But fig. 3b shows that quite some DE also occurs, due to the decreasing duty cycle of the reactivations governed by $\tau_r(t) \propto t$. The LFs are steep at the bright end, $N(L) \rightarrow \exp\left[(-L/L_b)^{\phi}/\phi\right]$; but at low $z$ the flat and slow $N_1(L, z)$ remains exposed and flattens the overall slope, not unlike the data referenced in Sect. 1.
Fig. 4b outlines the mass distribution of the relict BHs expected in most normal galaxies close to us, computed from \( M_{BH} = \int d t \frac{L(t)}{\eta c^2} \) with the luminosities evolving as above.

When the gas in the host is depleted, the remaining reservoir is in satellite galaxies cannibalized out of an initial retinue gradually used up. With this prevailing, \( L_b \sim \text{const} \) obtains with no LE (see fig. 2), while the DE is enhanced as shown in fig. 4a. The gas available per event \( M_{\text{gas}} \propto M_{\text{sat}} \) follows the dwarf galaxies distribution, to yield steeper LFs at the faint end. We expect such to be the case when \( M \lesssim 10^{-2} L_E/c^2 \) holds, with ADAF prevailing; we relate this regime to the X-ray LFs of the NLXGs as given by Hasinger 1997.

6. Conclusions and discussion

We conclude that the coherent, non-monotonic QS evolution, with its scales of a few Gyrs and overall duration for \( \sim 12 \) Gyr, calls for a coordinating role of the surrounding structures to govern the accretion onto massive BHs.

Remarkably, this is provided by the monotonic hierarchical cosmogony. Young host galaxies are assembled from subgalactic units, and then the mature hosts are packed into larger and larger groups where they still evolve for a while by interactions. Both the assemblage and the interactions perturb the host gravitational potential and cause, besides starbursts, first rapid growth of BHs, then accretion episodes inevitably petering out in rate and strength.

Thus the QS-galaxy connection is actually twofold. At low \( z \) much evidence relates AGN and QS hosts to interacting or to group environments. At high \( z \) one expects QSSs associated with subgalactic star-forming blocks just looming out; one such instance may be the region singled out by Fontana et al. 1997.
Figure 4.  

a) X-ray LFs from accretion of gas in satellite galaxies, with $\eta/\kappa = 10^{-4}$; from top $z = 1, 0.1$.  
b) Mass distribution of the relict BHs, compared with data: masses from Kormendy & Richstone 1995, and numbers from the bulge distribution after Franceschini et al. 1998.

In this view the QS evolution should be marked by number increase as $M_c(t)$ marches through the galactic range up to $5 \times 10^{12} M_\odot$; here the basic scale is $t_g$. The turning point occurs as $M_c(z)$ outgrows $5 \times 10^{12} M_\odot$ at $z \simeq 3 \pm 0.5$; then the number, and even more the luminosities, decrease on the stretching scale $\tau_r \propto t$. The LFs so computed are found to agree in some detail with the observations out to $z \simeq 5$, specifically for the hierarchy provided by the tilted CDM perturbation spectrum in the critical universe.

The predictions for $z > 5$ look rather dim; not many bright QSs are expected on the basis of the model successful at lower $z$ (see fig. 3a). Actually these predictions sensitively depend on the two obvious parameters: the threshold for DM condensations in the Press & Schechter mass function (in fig. 3a we use the canonical $\delta_c = 1.69$); the baryonic fraction $M_{BH}/M$ packed in BHs (this decreases with $M$ like $M^{2/3}$, but is partially balanced by the factor $(1 + z)^{2.5}$). The predictions for low $z$ and weak $L$, instead, depend on whether the main gas reservoir is in the host or in satellite galaxies, as shown by figs. 3b and 4a.

The quasar light history (of gravitational origin) computed from the above LFs is shown in fig. 1, and compared with the star light history (of thermonuclear origin) given by Madau 1997; the latter at $z \lesssim 1$ is mainly contributed by the faint blue galaxies, which Cavaliere & Menci 1997 interpret as starbursts in dwarfs interacting in large-scale structures. Then the similarity of the two histories at such $z$ reflects the basically similar run of the time scale $\tau_r \propto n_g^{-1}$ for interactions in dense environments, in spite of two differences: the environments are constituted by condensing LSS or by virialized groups, respectively; the FBG starbursts last longer than the nuclear activities.

Looking briefly at other hierarchical cosmogonies, the hot + cold DM perturbations – even when given all advantages like only 20% hot matter and suitable amplitude to fit the data at $z \simeq 4$ – produce at low $z$ far too many bright QSs, reflecting the later collapses of galaxies in this version of the hierarchy. In
very open universes with standard CDM perturbations, we find for \( z < 2 \) too few bright QSs, due to group formation frozen long before and to gas reservoirs already exhausted. Low-density but flat universes fare much better, nearly as the critical, tilted CDM case.

References

Bahcall, J.N., Kirhakos, S., Saxe, D.H. & Schneider, D.P. 1997, ApJ, 479, 642
Barnes, J.E. & Hernquist, L.E. 1991, ApJ, 370, L65
Bisnovatyi-Kogan, G.S. & Lovelace, R.V.E. 1997, ApJ, 486, L93
Boyle, B.J., Shanks, T. & Peterson, B.A. 1988, MNRAS, 235, 935
Bunn, E.F. & White, M. 1997, ApJ, 480, 6
Cavaliere, A., Giallongo, E., Padovani, P. & Vagnetti, F. 1988, ASPCS 2, 335
Cavaliere, A., Colafrancesco, S. & Scaramella, R. 1991, ApJ, 380, 15
Cavaliere, A. & Menci, N. 1997, ApJ, 480, 132
Cavaliere, A., Perri, M. & Vittorini, V. 1997, Mem SAIt, 68, 27 (CPV97)
Di Matteo, T. & Fabian, A.C. 1997, MNRAS, 286, L50
Disney, M.J. et al. 1995, Nature, 375, 150
Dunlop, J.S. 1997, preprint astro-ph/9704294
Fisher, K.B., Bahcall, J.N., Kirhakos, S. & Schneider, D.P. 1996, ApJ, 468, 469
Fontana, A., D’Odorico, S., Giallongo, E., Cristiani, S. & Petitjean, P. 1997, AJ in press
Franceschini, A., Vercellone, S. & Fabian, A.C. preprint astro-ph/9701129
Goldschmidt, P. & Miller, L. 1997, MNRAS, in press
Governato, F., Tozzi, P. & Cavaliere, A. 1996, ApJ, 458, 18
Haehnelt, M.G., Natarajan, P. & Rees, M.J. 1997, astro-ph/9712259 (HNR97)
Haiman, Z. & Loeb, A. 1997, astro-ph/9710208
Hasinger, G. et al. 1996, preprint “Interacting Galaxies, the X-ray View”
Hasinger, G. 1997, astro-ph/9712342
Ho, L.C., Filippenko, A.V. & Sargent, W.L.W. 1997, ApJ, 487, 568
Hutchings, J.B. & Neff, S.G. 1992, AJ, 104, 1
Kennefick, J.D., Djorgovski, S.G. & de Carvalho, R.R. 1995, AJ, 110, 2553
Köhler, T., Groote, D., Reimers, D. & Wisotzki, L. 1997, A&A, in press
Kormendy, J. & Richstone, D. 1995, ARA&A, 33, 581
La Franca, F. & Cristiani, S. 1997, AJ, 113, 1517
Madau, P. 1997, STSCI preprint 1183
Magorrian, J. et al. 1997, astro-ph/9708072
Peebles, P.J.E. 1993, “Principles of Physical Cosmology”, Princeton Univ. Press
Press, W.H. & Schechter, P.L. 1974, ApJ, 187, 425
Rafanelli, P., Violato, M. & Baruffolo, A. 1995, AJ, 109, 1546
Rees, M.J. 1997, preprint astro-ph/9701161
Schmidt, M., Schneider, D.P. & Gunn, J.E. 1995, AJ, 110, 68
Shaver, P.A. et al. 1996, Nature, 384, 439
Small, T.A. & Blandford, R.D. 1992, MNRAS, 259, 725
Steidel, C.S. et al. 1996, ApJ, 462, L17
Toomre, A. 1977, in *Evolution of Galaxies and Stellar Populations*, ed. B.M. Tinsley & R.B. Larson (Yale Univ. Obs.: New Haven) p. 401