THE TWOFOLD QUASAR-GALAXY CONNECTION

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The rise and the fall of the QS population are explained in terms of massive black holes forming/accreting during the assemblage of the host galaxies, and of accretion rekindled by interactions of the host with companions in a group. We compute the LFs out to $z = 6$. We also predict the masses of relict black holes to be found in many galaxies. We compare the histories of the QSO and of the star light.

1 The rise and fall of the quasars

The body of radio, optical and X-ray evidence supporting a genuine, if broad peak in the number of bright QSs around $z \simeq 3$ has been reviewed by Shaver et al. 1996. The QS population is found to rise in number during the first few Gyrs of the Universe life, down to epochs $z \simeq 3$; in the QS jargon, this is a negative DE toward increasing $z$. Later than $z \lesssim 3$ the population falls in cosmic epoch on a scale of $\simeq 2 - 3$ Gyr. This course has been interpreted as dominated by LE, but at least two additions are called for (see La Franca & Cristiani 1997): at the faint end the LFs grow higher with $z$, and require a considerable positive DE; the bright end of the LFs is flatter at low $z$, with more numerous bright objects than previously recognized.

That QSs as individual sources are powered by gas accretion onto a massive black hole has been argued many times, and direct evidence is now mounting (see Rees 1997). But accretion limited only by radiation pressure exponentiates on the short time scale $\eta t_E \simeq 4 \times 10^7$ yr. The coherent rise and fall of the QS population over most of the Universe lifetime requires extended coordination. We show this to be provided by the hierachical growth of structures, first as the host galaxies are built up, and then as groups form where the hosts interact with companions. The transition takes place just at $z \sim 3$; but in both dynamical regimes the symmetry of the gravitational potential is broken, and this provides conditions for fueling or for refueling the BHs.

2 BHs fueled by galaxy formation, and refueled by interactions

The hierarchical cosmogony envisages the typical density perturbation collapsing and virializing at the epoch $t$ to have a mass growing as $M_c \propto t^{4/(n+3)}$ when $\Omega = 1$; for Cold Dark Matter perturbations $n \simeq -2$ applies. A similar trend is retained when $\Omega_o < 1$ until the growth freezes out at $1 + z \simeq 1/\Omega_o$. 

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A subgalactic building block of DM with $M \sim 10^9 \, M_\odot$ allows a $10^6 \, M_\odot$ BH to form, involving a baryon fraction $\epsilon_* \sim 10^{-3}$ (HR 93). The galaxy assemblage goes on chaotically with angular momentum $j \neq \text{const}$, the gas accretion is only Eddington-limited and produces luminosities $L \sim L_E \propto M_{BH} \sim \epsilon_* M$.

The transitional mass from a large galaxy to a small group is $5 \times 10^{12} \, M_\odot$. In the hierarchical cosmogony this corresponds on average to $z_* \simeq 3 \pm 0.5$, depending on the cosmology and on the detailed perturbation model. Such values match the range where the bright QSs peak, corroborating our view.

In groups, many simulations (see Governato et al. 1996) have shown interactions to be frequent and effective, due to the high density of galaxies $n_g \propto \rho_U(z)$, and to the velocity dispersion $V \propto M_c^{(1-n)/12} \sim t$ being still close to the galaxian $v_g$. Nearly grazing encounters occur on the time scale $\tau_r \sim 1/n_g \pi r_g^2 V$, and produce merging (Cavaliere & Menci 1997) or other strong interactions which perturb the potential and again cause $j \neq \text{const}$. Indeed, aimed simulations (see Barnes & Hernquist 1991) show the gas in both interaction partners to lose $j$ and be driven down to the main galactic nucleus.

This view is supported by the extensive astronomical evidence showing individual QSs in hosts either engaged in merging and in current interactions, or having close companions even submerged within the galaxian body (see Hutchings & Neff 1992, Disney et al. 1995, Bahcall et al. 1996, Hasinger et al. 1996). The statistics ranges from a lower limit $\sim 15\%$ (Rafanelli et al. 1995) up to $\sim 1/2$ of the hosts (Bahcall et al. 1996); the average QS environment comprises $\sim 10 - 20$ galaxies (Fisher et al. 1996).

3 The evolution of the luminosity function

To include such bimodal fueling of the same engines, our LFs (see also CPV 97) comprise at any $L, z$ two components: $N(L, z) = N_1(L, z) + N_2(L, z)$.

$N_1$ accounts for BHs newly formed on the scale $t_{dyn}$ of the host buildup a process dominant for $M \lesssim 5 \times 10^{12} \, M_\odot$ and $z \gtrsim 3$. It is computed on the basis of the Press & Schechter 1974 mass function $N(M, z)$, using the Eddington-limited $L \propto M$ similarly to HR 93, but with two crucial differences: we let $M_{BH}$ follow the hierarchical growth of the host galaxy; we consider the probability $\propto \rho_U^2(z)$ of forming BHs as a prefactor of $N(L, z)$ rather than of $M_{BH} \propto L$.

$N_2$ comprises BHs reactivated by interactions, and is dominant in structures (especially in groups) with $M > 5 \times 10^{12} \, M_\odot$, at $z \lesssim 3$. The BHs restart their bright career from a low luminosity distributed after $f(L)$; the reactivation of the $N_r$ dormant BHs occurs with probability $\propto 1/\tau_r$. Now the activity is supply-limited, reaches a top $L_b$ to statistically fade off on the time scale...
Figure 1: The LFs at \( z = 6.5, 4.5, 3 \) (panel a, from bottom to top), and at \( z = 2.4, 1.0, 0.5 \) (panel b, from top to bottom) computed for QSO forming in the critical universe from tilted CDM density perturbations, and then accreting host gas upon interactions; optically selected data as in CPV 97. Panel c shows the mass distribution of dormant BHs expected from this model at the center of many normal galaxies; for the data, see CPV 97. Panel d compares the history of the light density from QSOs with bolometric \( L > 10^{45} \) erg/s, to that of the star light produced by Madau 1997; the normalization of the former is actually \( \sim 1/30 \).

\[ \tau_L \propto L_b/L. \] All that is expressed by the rate equation

\[ \partial_t N_2 + \partial_L (LN_2) = f(L) N_r/\tau_r - N_2/\tau_L. \] (1)

To close the argument, \( N_r \) is made up by the last term integrated over \( L \), and by the newly formed BHs described by \( N_1 \). Thus \( N_2 \) arises from \( N_1 \) and requires no independent normalization; \( N_1 \) is normalized to the data at \( z = 4 \), and implies today about one relict BH per few bright galaxies.

4 Conclusions and discussion

Fig. 1a shows the LFs at high \( z \). The prediction at \( z = 6 \) is sensitive to the threshold \( \delta_c \) for collapse in the Press & Schechter formula; this is taken here to decrease slowly with \( z \) from the value 1.7, as indicated by recent simulations.
Fig. 1b represents the low-z behavior when the accreted gas is provided mainly by the host reservoir (say, a constant fraction used up in each interaction); then $-\dot{M}_{\text{gas}}/M_{\text{gas}} \simeq \tau_{\alpha}^{-1} \simeq -\dot{L}_b/L_b$ holds, to yield $L_b(t) \propto t^{t_{\alpha}/\tau_{\alpha}}$. With $\tau_{\alpha} \simeq 6 \text{ Gyr}$ (scaled to groups from the classic census of local interacting galaxies by Toomre 1977), the result is $L_b \propto (1 + z)^3$. This implies LE dominant at $z < 3$, and LFs flattened by L increasing over the flyby time $2r_g/V \sim \text{few} \times 10^5 \text{ yr}$. But fig. 1b shows that some DE also occurs, since the frequency of the effective interactions peter off when groups aggregate into clusters with high $V$. Fig. 1c shows the mass distribution predicted for the relict BHs in many local, currently inactive galactic nuclei.

Alternatively, the gas may reach the nucleus of a large galaxy mainly from satellites cannibalized out of an initial retinue gradually depleted. Then $L_b \sim \text{const}$ obtains with no LE, while the DE is enhanced; the gas mass $\propto M_{\text{sat}}$ follows the satellite distribution and yields steeper LFs at the faint end.

In either case, one ends up with the QS light history (of gravitational origin) shown in fig. 1d, and compared with the star light history (of thermonuclear origin) produced by Madau 1997; at $z \lesssim 1$ this is mainly contributed by the faint blue galaxies, which Cavaliere & Menci 1997 interpret as starbursts in dwarfs interacting in LSS. The similar run at such $z$ corroborates the view that interactions in dense environments (condensing LSS or virialized groups, respectively) drive much of the light illuminating the $z \sim 1$ Universe.

1. Bahcall, N.J., Kirhakos, S., Saxe, D.H. & Schneider, D.P.: 1996, preprint
2. Barnes, J.E. & Hernquist, L.E.: 1991, Astrophys. J. L. 370, L65
3. Cavaliere, A. & Menci, N.: 1997, Astrophys. J., 480, 132
4. Cavaliere, A., Perri, M., Vittorini, V.: 1997, Mm SAIt, 68, 27 (CPV 97)
5. Disney, M.J. et al.: 1995, Nature 375, 150
6. Fisher, K.B., Bahcall, J.N., Kirhakos, S. & Schneider, D.P.: 1996, Astrophys. J. 468, 469
7. Governato, F., Tozzi, P. & Cavaliere, A.: 1996, Astrophys. J. 458, 18
8. Haehnelt, M.G. & Rees, M.J.: 1993, MNRAS 263, 168 (HR 93)
9. Hasinger, G. et al.: 1996, preprint “Interacting Galaxies, the X-ray View”
10. Hutchings, J.B. & Neff, S.G.: 1992, Astron. J. 104, 1
11. La Franca, F. & Cristiani, S.: 1997, submitted to Astron. J
12. Madau, P.: 1997, STSCI preprint 1183
13. Press, W.H. & Schechter, P.L.: 1974, Astrophys. J. 187, 425
14. Rafanelli, P., Violato, M. & Baruffolo, A.: 1995, Astron. J. 109, 1546
15. Rees, M.J.: 1997, “Astrophysical Evidence for Black Holes”, preprint
16. Shaver, P.A. et al.: 1996, Nature, 384, 439
17. Toomre, A.: 1977, in Evolution of Galaxies and Stellar Population, ed. B.M. Tinsley & R.B. Larson (Yale Univ. Obs.: New Haven) p. 401
To appear in Proc. 12th Potsdam Cosmology Workshop, Sept. 1997, “Large-Scale Structures: Tracks and Traces”, eds. V. Müller et al., World Scientific, Singapore