The Large-Scale Structure view on the Galaxy-Quasar-AGN connection

Manuela Magliocchetti
INAF, Osservatorio Astronomico di Trieste, Via Tiepolo 11, 34100, Trieste, Italy

Combined investigations of the clustering properties of galaxies of different spectral type and high-redshift quasars strongly suggest local ellipticals to be the parent population of optically bright Active Galactic Nuclei (AGN). However, the picture gets more blurred when one extends the analysis to that class of AGNs which show enhanced radio emission. Objects belonging to this class in fact are found to be associated with structures which are about an order of magnitude more massive than those that host radio-quiet AGNs. Also, masses for the black holes engines of radio-enhanced AGN emission turn out to be systematically higher than those which fuel 'normal' quasars. On the other hand, the level of radio-activity in radio-luminous objects does not seem to be connected with black hole/host galaxy mass, at variance with what found in the optical case. These results, together with evidences for different cosmological evolutions of different types of AGNs pose a serious challenge to all those models aiming at providing a unified picture for black hole-powered sources.

1 The Quasar-Galaxy Connection

A careful analysis of the clustering properties of optically selected quasars has been performed by [1]. These authors have concentrated on \( \sim 15000 \) objects taken from the 2dF Quasar Redshift Survey [2] in the redshift range \( 0.8 \leq z \leq 2.1 \). Investigations of the projected spatial correlation function (see Figure 1) was performed by means of the so-called Halo Occupation Model. Its main quantity, the Halo Occupation Number (HON) \(< N(M) >\), provides the mean number of sources brighter than some luminosity threshold hosted by a dark matter halo of chosen mass and, for halo masses greater than some chosen value \( M_0 \), can be written as follows:

\[
< N(M) > = N_0 (M/M_0)\alpha.
\] (1)

Combinations of values for the three parameters \( M_0, N_0, \alpha \), presented in equation (1) have been considered so to match the observations in three different redshift ranges, in order to investigate any possible evolution of the quasar properties with look-back time. The main results, presented in Table 1 and in the left-hand panel of Figure 1, indicate that the typical minimum masses of haloes hosting optically selected quasars do not show great variations with redshift and lie in the narrow range \( 10^{12.2} - 10^{12.7} M_\odot \). Also, the way the number of quasars hosted by a halo increases with its mass can be considered as constant (\( \alpha \simeq 0.7 \)) with good approximation. As a matter of fact, [1] found that the 2dF QSO clustering data can be easily described if one assumes values for the halo occupation number which stay constant in the whole redshift range covered by the data, denoting no evolution for at least some of the main structural properties connected to the presence and activity of quasars.
Table 1: Best-fitting values for the Halo Occupation Number (1) in the case of 2dF early-type galaxies (column 1) and 2dF quasars at different redshifts (columns 2-4).

|                  | Early - < z > ≥ 0.1 | QSOs - < z > ≥ 1.1 | QSOs - < z > ≥ 1.5 | QSOs - < z > ≥ 1.9 |
|------------------|----------------------|---------------------|---------------------|---------------------|
| \( \alpha \)     | \( \approx 1 \)      | \( \alpha = 0.4^{+0.3}_{-0.3} \) | \( \alpha = 0.6^{+0.4}_{-0.4} \) | \( \alpha = 1.1^{+0.7}_{-0.4} \) |
| \( \log[M_0/M_\odot] \) | \( \approx 12.6 \) | \( \log[M_0/M_\odot] = 12.2^{+0.2}_{-0.3} \) | \( \log[M_0/M_\odot] \sim 12.5^{+0.2}_{-0.3} \) | \( \log[M_0/M_\odot] \sim 12.7^{+0.3}_{-0.4} \) |

Figure 1: Left-hand panel: Projected correlation function of 2dF quasars in different redshift bins as indicated in the panels. The dashed lines show the best power-law fit to the data, while the solid curves denote the best fits obtained within the HON framework. Right-hand panel: Best Halo Occupation Number (solid lines) and confidence intervals (dashed lines) as derived by\(^1\).

The HON estimates summarized in Table 1 are in extremely good agreement with those obtained by\(^3\) in the investigation of the clustering properties of 2dF galaxies of early spectral type as measured by\(^4\). By again working within the HON framework, these authors indeed find that the projected correlation function of early-type galaxies (left-hand panel of Figure 2) can be very nicely described by assuming local elliptical galaxies to be hosted by haloes always more massive than \( \sim 10^{12.6} M_\odot \), with a mean number increasing linearly with halo mass (\( \alpha \approx 1 \), cfr right-hand panel of Figure 2 and Table 1). We note that such an agreement between halo occupation properties of local (\( z \leq 0.2 \)) elliptical galaxies and intermediate-to-high redshift quasars is even more striking as the functional form adopted by\(^3\) for \( \langle N(M) \rangle \) shows a number of differences when compared to that presented in equation (1).

The above results then imply that the structures which host QSOs at high redshifts are the same as those harbouring elliptical galaxies in the local universe. The picture that emerges purely from Large-Scale Structure studies is that of a strong evolutionary connection between local elliptical galaxies and high-redshift quasars, whereby the former class of sources can be identified as the parent population of bright, optically active AGNs. The chances to find an elliptical galaxy in its AGN phase is however low (in the redshift range considered by\(^\text{II} \) the ratio between the number of galaxies hosting a quasar to that of the whole galaxy population is \( N_0 \approx 10^{-3} \)), due to the limited life-time \( t_Q \) of the quasar phenomenon. \( t_Q \) is estimated by\(^\text{II} \) to be \( \sim 7 \cdot 10^7 \) yr at \( z \approx 2 \), showing some hint for a decline at lower redshifts, possibly due to the more limited reservoir of gas needed to fuel the black hole (BH) hosted in the galaxy centres.
Figure 2: Left-hand panel: Projected correlation function of local 2dF early-type galaxies. The solid line shows the best-fit to the data as calculated by\(^3\). The corresponding best HON is indicated in the left-hand panel by the red-solid line.

Figure 3: Left-hand panel: Projected correlation function of local 2dF radio galaxies as obtained by\(^5\). The dashed lines indicate models for the correlation function of dark matter halos with masses respectively greater than \(10^{10}M_\odot\) (bottom curve) to \(10^{14}M_\odot\) (top curve). Left-hand panel: Redshift-space correlation function of radio galaxies of different luminosity. Open squares are for \(\log(P) > 22\) [W/Hz/sr], filled dots for \(\log(P) < 22\) [W/Hz/sr].

2 Radio AGN

Having dealt with optically selected quasars, we can now move on to investigating the properties of the broader class of Active Galactic Nuclei. In particular, we will concentrate our attention on radio-active sources, trying to tackle the following issues:

– What is the connection between optical AGNs and radio sources?
– Is the evolution of radio-active sources the same as that of optical AGNs?
– Is radio-activity related to short-scale and/or large-scale processes?
– And ultimately: what triggers radio-activity?

Once again, investigations of the large-scale properties of radio-active sources proves to be a very important diagnostic tool towards a correct interpretation of the AGN phenomenon. For instance, analyses of the clustering properties of the population of local radio galaxies performed by\(^5\) show that the correlation function of such sources has an amplitude which is about twice that found for 'normal' elliptical galaxies\(^4\). Furthermore, comparisons with models (cfr left-hand panel of Figure 3) clearly indicate that local radio-active AGN have to reside in haloes more massive than \(\sim 10^{13.5}M_\odot\). This figure is about a factor 10 higher than that found for optically selected quasars in Section 1. If we use the relation developped by\(^6\) the above findings imply masses for the black holes powering the quasar phenomenon to be about an order of magnitude smaller than those fuelling radio galaxies \((\sim 10^8M_\odot \text{ vs } \sim 10^9M_\odot)\).
Figure 4: Left-hand panel: Angular two-point correlation function of NVSS radio sources as obtained by\textsuperscript{8}. The dashed lines indicate models for $w(\theta)$ based on halo masses which decrease with look-back time as $M_\ast$. From bottom to top these have been obtained for local values of the effective halo mass between $10^{13}$ and $10^{15} h_0^{-1} M_\odot$. The bottom panel illustrates the corresponding time evolutions of the bias function. Left-hand panel: bias function $b(M_{\text{eff}}, z)$ as a function of redshift. Data points show the results obtained for optical quasars by\textsuperscript{1,12,13}, while the dotted curve illustrates the best-fit to the observations. The dashed curve reproduces the trend for the bias function found in the case of NVSS radio sources as reported in the bottom-right panel. Work from\textsuperscript{10}.

Another important piece of information can be obtained through the study of the clustering properties of sources with different radio luminosities. The results are illustrated in the right-hand panel of Figure 3 and show that, within the errors, differences in the redshift-space correlation function $\xi(s)$ of radio galaxies belonging to different classes of radio luminosity are negligible. If we then once again connect the clustering properties of bright and faint radio sources with the masses of the haloes which host them, and also refer to the results presented so far, we can conclude that there seems to be the need for a threshold halo (BH) mass to produce significant emission from AGN. However, once radio activity is onset, there is no evidence for a connection between radio luminosity and dark matter content (BH mass). We note that a strong back-up to the above statement comes from the results of\textsuperscript{17} who estimated BH masses directly from the spectra of a sub-sample of optically selected quasars with intense radio emission and found them not only to be independent on the level of radio activity, but also to be systematically more massive than those associated to the whole quasar population ($< M_{\text{BH}}^{\text{RL}} > \sim 10^{8.6} M_\odot$ vs $< M_{\text{BH}}^{\text{Q}} > \sim 10^{8.3} M_\odot$).

Some more interesting constraints on the behaviour of radio sources can be obtained by investigating the clustering properties of the whole radio population, regardless of their redshift distribution. The angular two-point correlation function $w(\theta)$ of sources brighter than 10 mJy as measured by\textsuperscript{8} in fact presents the puzzling behaviour of a power-law trend which extends up to angular scales of the order of $\sim 10$ degrees (left-hand panel of Figure 4). The redshift distribution $N(z)$ of radio sources with $S_{1.4\text{GHz}} \geq 10$ mJy is predicted\textsuperscript{12} to be quite broad, spanning the $\sim 0 - 4$ redshift range, with a peak at $z \sim 1$. The maximum contribution to the angular correlation function $w(\theta)$ is then expected to originate from those sources which identify the $z \sim 1$ peak of $N(z)$. On the other hand, the spatial correlation function $\xi(r)$ for the dark matter is shown to become negative for comoving separations $r \geq 100$ Mpc (the exact value depending on the adopted cosmology) which, for a median redshift $z \sim 1$, corresponds to $\theta \sim 2$ degrees. It then follows that if one assumes constant masses for the dark matter halos which host radio sources as it was in the case of optically-selected quasars, it is impossible to explain the observed positive tail of $w(\theta)$ beyond $\sim 2$ degrees. We note that this problem is not alleviated either by adding to the total $w(\theta)$ a contribution from local star-forming galaxies or by adopting different halo masses. Even variations of the background cosmology (performed by considering different values for the parameters $h_0$, $\Omega_0$ and $\Omega_b$) do not manage to reconcile
models with observations (for a detailed approach to the above issues see\cite{10}).

The only possible way out to this problem is to invoke a clustering which was weaker in
the past. This can be done if we assume the characteristic mass of halos hosting radio sources
to be proportional to $M_*$, i.e. the typical mass-scale when fluctuations collapse to form bond
structures\cite{11}. In this case, the predicted $w(\theta)$ provides a much better description to the data
on all scales (cfr dashed curves in Figure 4). The best-fit correlation is provided in the standard
WMAP cosmological scenario by a local mass for the halos hosting radio sources $M_{\text{eff}} \sim 10^{15}M_\odot$,
showing once again that – at least locally – radio sources trace the distribution of the most
massive structures in our universe such as clusters of galaxies.

Taken at face value, the above result points to different evolutionary properties for different
classes of AGNs. In fact, while optically selected quasars are associated to halos with effective
masses $M_{\text{eff}} \sim 10^{13}M_\odot$ which stay constant with look-back time up to the highest probed
redshifts ($z \sim 2.5$, cfr the right-hand panel in Figure 4), masses for those hosting radio sources
are found to decrease with $z$. Indeed, radio sources seem to reside within the largest structures
which collapse at any given epoch; in a narrow redshift interval around $z \sim 1.5$ these correspond
to the hosts of optical quasars, while in the local universe they can be identified with groups
and clusters of galaxies.

3 Conclusions

The results presented in this work and mainly based on Large-Scale Structure studies can be
summarized as follows:

1. There exists a strong evolutionary connection between high-z quasars and local elliptical
galaxies.

2. Local radio galaxies are associated to structures which are about a factor of 10 more
massive than those which host optically-selected quasars. They are also most likely fuelled
by heavier BHs.

3. In radio-active sources there does not seem to be any connection between radio luminosity
and BH/halo mass.

4. The clustering of radio sources is found to be weaker in the past. This implies radio-active
objects to be hosted by halos with masses which decrease with look-back time at variance
with the quasar case which requires $M_{\text{eff}} \sim \text{const}$ at all redshifts probed by available
surveys. These two classes of objects seem to be associated to the same kind of structures
only at $z \sim 1.5$.

The above conclusions raise a number of issues that need to be addressed whenever inves-
tigating possible connections – both on large and on small scales – between radio sources and
optically-selected AGNs such as quasars. In fact, these two classes of objects are found to reside
in different structures, be fuelled by black holes of different masses and exhibit different cosmo-
logical evolutions, results which pose a serious challenge to all those models aiming at providing
a unified picture for black hole-powered sources.

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