Joint formation of bright quasars and elliptical galaxies in the young Universe

Pierluigi Monaco

Dipartimento di Astronomia, Università di Trieste, and SISSA, Trieste

Paolo Salucci and Luigi Danese

SISSA, Trieste

Abstract. We show that the mass function of black holes expected from the past quasar activity (both visible and obscured) is consistent with the number of dormant black holes found in the bulges of nearby galaxies. The joint formation of quasars and bulges is addressed by means of an analytical model for galaxy formation, based on the hierarchical clustering of cold dark matter halos. The model is able to reproduce the main statistical properties of both populations under the hypotheses that (i) star formation and quasar shining follow an anti-hierarchical order, and (ii) galaxy morphology and final black hole mass are determined by the same physical process.

1. Introduction

Quasars, and AGN in general, are often supposed to be powered by accretion of gas into supermassive black holes (BHs). In this case, large dormant BHs are expected in the nuclei of nearby galaxies (Soltan 1982; Rees 1984; Cavaliere & Padovani 1986). Assuming accretion at a known fraction of the Eddington rate and efficiency of radiation of 10\% in units of $mc^2$, it is possible to estimate the expected mass function of dormant BHs. This mass function implies a number density of large BHs ($>10^8 M_\odot$) compatible with the hypothesis that a BH is present in each bright bulge.

Recent detailed observations of the cores of nearby galaxies have lead to the discovery of massive dark objects in most cases (Magorrian et al. 1998; van der Marel 1999). Even though many details are still uncertain, many authors agree in claiming a correlation between the mass of the massive dark object and the host bulge. Interpreting these dark objects as the expected dormant BHs, the BH–bulge correlation strongly suggests a connection between quasar activity and the formation of galactic bulges.

2. The mass function of dormant black holes.

It is assumed that the accretion of matter onto a BH of mass $M_\bullet$ is a fixed fraction $f_{\text{ED}}$ of the Eddington rate, so that the quasar luminosity is $L = f_{\text{ED}}L_{\text{ED}}$, where

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Figure 1. Mass function of dormant BHs (see text for details).

$L_{\text{ED}} \simeq 3.4 \times 10^4 (M_\bullet / M_\odot) L_\odot$. The efficiency of accretion $f_{\text{ED}}$ is assumed to increase from 0.1 for the smallest BHs ($\sim 10^6 M_\odot$) to 1 for the largest ones ($\sim 10^{10} M_\odot$). Then, the mass function of dormant BHs is calculated by integrating the luminosity function of quasars (see Salucci et al. 1999a for details). We assume that a significant fraction of AGNs are heavily obscured, and give the dominant contribution to the hard X-ray cosmological background (see, e.g., Celotti et al. 1995; Comastri et al. 1995; Fiore et al. 1998). We include such objects using the model of Comastri et al. (1995). The resulting expected mass function of dormant BHs is shown in Fig. 1 (dashed line), for $H_0 = 70$ km/s/Mpc and $\Omega = 1$.

The mass function of dormant BHs residing in nearby galaxies is estimated with two independent methods (see Salucci et al. 1999a for details). Firstly, the mass function of galactic bulges is convolved with a fiducial BH – bulge relation (a lognormal, with width 0.3 dex and average $M_\bullet / M_\text{bulge} \sim 3 \times 10^{-3}$). Fig. 1 shows the resulting mass function (continuous line). Secondly, exploiting the correlation between radio power from the core of elliptical galaxies and BH mass ($P \propto M_\bullet^\alpha$, where $\alpha \sim 2 - 2.2$, see also Franceschini et al. 1998), the radio luminosity function of elliptical cores is convolved with a BH – radio power relation to obtain another estimate of the mass function of the dormant objects. The result is again shown in Fig. 1 (points with errorbars).

3. A favoured scenario

The three determinations of the mass function of dormant BHs agree for reasonable values of the parameters involved. This highlights a dichotomy (in a statistical sense) in the behaviour of BHs. Larger objects ($M > 10^8 M_\odot$) are
hosted in ellipticals, shine as bright quasars at high redshift, almost at the Eddington luminosity, are hardly reactivated and hardly obscured, while smaller BHs ($M < 10^8 M_\odot$) are hosted in the bulges of spiral galaxies, shine also at low redshift with a lower luminosity (in Eddington units), and may be reactivated and obscured.

The abundance of BHs in the bulges of spiral galaxies is more difficult to estimate. Upper limits have been determined by Salucci et al. (1999b) by analyzing nearly a thousand rotation curves for spirals.

4. A model for the joint formation of quasars and elliptical galaxies

We have constructed an analytical model for the joint formation of ellipticals and quasars in the framework of hierarchical CDM models. The details are given in Monaco, Salucci & Danese (1999).

In a bulge, quasar activity and the main burst of star formation, which mark the main “shining phase” of a galactic dark matter halo, are likely to be close in time (see, e.g., Hamann & Ferland 1993; see also Best, these proceedings). It is supposed that the shining phase of a galactic halo is delayed with respect to its dynamical formation. This delay is assumed to be small for the halos corresponding to large ellipticals, and increasingly larger for smaller halos. In this way the hierarchical order is inverted for halo shining. This is done to reproduce the apparent anti-hierarchical evolution of quasars while preserving a correlation between bulge and BH mass.

The mass of the BH formed during the shining phase is assumed to depend on the halo mass, and to be modulated by the same variable which determines the morphological type, so as to obtain a BH-bulge relation. This variable is
Figure 3. Quasar luminosity functions at various redshifts ($H_0 = 70$ km/s/Mpc, $\Omega = 0.3$, $\Omega_\Lambda = 0.7$). The optical luminosity function is taken from Pei (1995). Following Comastri et al. (1995), the contribution of obscured objects is estimated from the X-ray luminosity function of Boyle et al. (1993). The curve named “ALL” gives the total contribution of optical and obscured objects. At $z = 4.4$ the data points of Kennefick et al. (1996) (denoted by stars) are reported.
assumed to be either the spin of the dark matter halo or the fraction of the merging masses at the formation time.

The model reproduces successfully the main observable quantities relative both to elliptical galaxies and quasars; see Monaco et al. (1999) for details. The results shown in this paper are for a flat CDM model with $\Omega = 0.3$, cosmological constant and $H_0 = 70$ km/s/Mpc. Fig. 2 shows the predicted mass function for the dark matter halos of ellipticals, compared with that inferred from the luminosity function and reasonable hypotheses on the mass-to-light ratios of ellipticals. Fig. 3 shows the comparison between the predicted and observed quasar luminosity functions at different redshifts. The data are taken from Pei (1995), Boyle et al. (1993) ($z = 1$ to 3) and Kennefick, Djorgovski and Meylan (1996) ($z = 4.4$).

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References

Boyle B. J., Griffiths R. E., Shanks T., Stewart G. C., Georgantopoulos I., 1993, MNRAS, 260, 49
Cavaliere A., Padoan P., 1988, ApJ, 333, L33
Celotti A., Fabian A. C., Ghisellini G., Madau P., 1995, MNRAS, 277, 1169
Comastri A., Setti G., Zamorani G., Hasinger G., 1995, A&A, 296, 1
Fiore et al. 1998, Nature, in press
Franceschini A., Vercellone S., Fabian A., 1998, MNRAS, 297, 817
Hamann F., Ferland G., 1993, ApJ, 418, 11
Kennefick J.D., Djorgovski S.G., Meylan G., 1996, AJ, 11, 1816
Magorrian J., Tremaine S., Richstone D., Bender R., Bower G., Dressler A., Faber S.M., Gebhardt K., Green R., Grillmair C., Kormendy J., Lauer T., 1998, AJ, 115, 2285
Monaco P., Salucci P., Danese L., 1999, MNRAS, in press (astro-ph/9907095)
Pei Y.C., 1995, ApJ, 438, 623
Rees, M. J., 1984, ARA&A, 22, 471
Salucci P., Szuszkiewicz E., Monaco P., Danese L., 1999a, MNRAS, 307, 637
Salucci P., Ratnam C., Monaco P., Danese L., 1999b, MNRAS, submitted (astro-ph/9812485)
Soltan A., 1982, MNRAS, 200, 115
van der Marel R.P., 1999, AJ, 117, 744