On the relationship between galaxy formation and quasar evolution

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ABSTRACT

We compare the evolution with cosmic time of the star formation rate per comoving volume in galaxies and of the volume emissivity due to active galactic nuclei, in an attempt to understand the relationship between black hole accretion and the formation of the surrounding structure. We find an interesting similarity between the evolution rates for the total populations of galaxies and AGN, which indicates that, on average, the history of black hole accretion follows that of stellar formation in the host galaxies. Similarly, the evolution of luminous quasars parallels that of the stellar populations in massive spheroidal galaxies, in keeping with the locally established association of supermassive black holes and galactic bulges. We finally comment on our finding that high-luminosity, high-mass systems evolve on a shorter cosmic time-scale than lower mass ones; to explain this, theories of structure formation based on the gravitational collapse of dark matter haloes must be complemented with a detailed description of the dynamical processes in the baryonic component, which dominate the formation and evolution in high-density environments.

Key words: galaxies: active – galaxies: evolution – galaxies: formation – quasars: general – cosmology: observations.

1 INTRODUCTION

For a long time, quasar evolution and galaxy formation have been seen as quite unrelated subjects of observational cosmology. In addition to the difficulty of sampling homogeneous redshift intervals for the two source populations, the main reason for this has been a lack of understanding of the physical processes ruling the quasar phenomenon and galaxy formation and evolution.

In this context, an important discovery by the refurbished Hubble Space Telescope (HST) was that most (if not all) massive galaxies in the local Universe harbour a nuclear supermassive (\( \sim 10^7 \text{–} 10^9 M_\odot \)) dark object (probably a black hole), with a mass proportional to that of the host spheroid (\( M_{\text{BH}} = (0.002 \text{–} 0.005) M_{\text{spheroid}} \)); Kormendy & Richstone 1995; Faber et al. 1997; Magorrian et al. 1998]. This is indeed the prediction of the canonical model for active galactic nuclei (AGN) – assuming energy production by gas accretion on to a supermassive black hole – and is consistent with evolutionary schemes that interpret the quasar phase as a luminous short-lived event occurring in a large fraction of all normal galaxies, rather than one concerning a small minority of ‘pathological’ systems (e.g. Cavaliere & Padovani 1989). This association of nuclear massive dark objects with luminous spheroids is also directly proven by the HST out to moderate redshifts (\( z = 0.4 \)), where the host galaxies of radio-quiet and radio-loud quasars are found to be large massive ellipticals (e.g. McLure et al. 1999).

As far as distant galaxies are concerned, important progress has been made in the characterization of the star formation history as a function of redshift (Lilly et al. 1996; Madau et al. 1996). Deep HST imaging has also allowed us to characterize this history as a function of morphological type, for both cluster (Stanford, Eisenhardt & Dickinson 1998) and field galaxies (Franceschini et al. 1998).

Interpretations of the relationship between quasar activity and galaxy formation have been attempted in the framework of the hierarchical dark matter cosmogony (e.g. Haehnelt, Natarajan & Rees 1998). However, the QSO–galaxy connection is still enigmatic in several respects. In particular, while hierarchical clustering seems to account successfully for the onset of the quasar era at \( z = 3 \) (assuming that supermassive black holes form in proportion to the formation of dark matter haloes), the progressive decay of the quasar population at lower \( z \) (the QSO evolution) is not accounted for as naturally, and requires a substantially more detailed physical description (e.g. including the role of galaxy interactions: see Cavaliere & Vittorini 1998).

To provide further constraints on this interpretative effort, we consider here the most detailed information available on the evolutionary histories of the AGN emissivity and of the stellar formation rate in galaxies.

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populations in galaxies. The available information on the evolution of the star formation rate (SFR) is summarized in Section 2, and compared in Section 3 with that of AGN emissivity. Some consequences, in particular concerning the stellar and black hole remnants of past activity, and implications for models of structure formation are discussed in Section 4, while Section 5 summarizes our conclusions.

2 STELLAR FORMATION HISTORIES OF GALAXY POPULATIONS

The systematic use of the Lyman ‘drop-out’ technique to detect \( z > 2 \) galaxies (Steidel, Dickinson & Persson 1994), combined with spectroscopic surveys of galaxies at \( z \leq 1 \) (Lilly et al. 1996) and H\( \alpha \)-based measurements of the present-day SFR, have allowed determination of the evolution of the SFR in galaxies over most of the Hubble time (Madau et al. 1996). Figs 1 and 2 summarize some results of these analyses (for two values of \( q_0 \)) in the form of small filled circles, where the SFR is measured from fits of the UV rest-frame flux (assuming a Salpeter initial mass function with low-mass cut-off \( M_{\text{low}} = 0.1 M_\odot \)). We see, in particular, an increase by a factor of \( \sim 10^2 \)–20 of the SFR density going from \( z = 0 \) to \( z = 1 \–1.5 \).

The main uncertainty in these estimates is due to the (a priori unknown) effect of dust, extinguishing the optical–UV flux and plaguing the identification of distant reddened galaxies in the ‘drop-out’ catalogues. Corrections for this effect have been estimated to range from 1 to 3 mag, and mostly apply above \( z > 1 \). Although rather uncertain at the moment, the SFR density above redshift 1 seems to stay roughly constant up to \( z = 3 \) (the data point at \( z = 3 \) in Fig. 1 comes from Meurer, Heckman & Calzetti 1999).

Exploiting the exceptional imaging quality and spectral coverage available in the Hubble Deep Field, Franceschini et al. (1998) have analysed a sample of morphologically selected early-type galaxies with \( z < 1.3 \). By fitting synthetic galaxy spectra to these data, it has been possible to estimate the baryonic mass and age distribution of stellar populations, and hence the star formation history per comoving volume (shown as hatched regions in Figs 1 and 2); the evolutionary SFR density of early-type field galaxies is roughly constant at \( z \approx 1.5 \), while showing a fast convergence at lower redshifts (correspondingly, 90 per cent of stars in E/S0 galaxies have been formed between \( z = 1 \) and 3 for \( q_0 = 0.15 \), and between \( z = 1 \) and 4 for \( q_0 = 0.5 \)). This evolutionary pattern is quite different from that of the general field population (small circles in Figs 1 and 2), which displays a much shallower dependence on cosmic time.

We note that at \( z > 2 \) the uncertainties in all estimates of the SFR become very serious. The SFR estimate of early-type galaxies by Franceschini et al. is based on fits to the spectral energy distributions (SEDs) of galaxies at \( z < 1.3 \), and becomes uncertain at \( z > 2 \). Similar problems affect the SFR estimates for the Lyman ‘drop-out’ galaxies, because of the reddening problem. The present analysis will therefore mostly concentrate on data at \( z < 2 \).

Thus galaxies with early morphological types – dominating the galaxy populations in high-density environments – show an accelerated formation history, while later types, more typical of low-density regions, are slower in forming their stellar content. In Figure 1. Comparison of the redshift evolution of AGN emissivity per comoving volume (right-hand axis) with the evolution of the SFR in galaxies (left-hand axis), for \( q_0 = 0.5 \). Small filled circles show the evolutionary SFR of field galaxies estimated from conversion of the rest-frame optical–UV flux to SFR. The hatched region describes the evolution of the SFR in field galaxies morphologically classified as ellipticals and SOs by Franceschini et al. (1998). The filled squares are the 0.5–2 keV comoving volume emissivities (in erg s\(^{-1}\) Mpc\(^{-3}\)) of high-luminosity AGN (\( L_{0.5-2\text{keV}} = 10^{44.25} \) erg s\(^{-1}\); see Table 1). The top two lines show the 0.5–2 keV volume emissivities of the total AGN population (normalized by the same factor), based on the LDDE1 and LDDE2 models producing 60 and 90 per cent of the XBR at 1 keV, respectively. The thick dashed line is the volume emissivity of optical quasars from Schmidt, Schneider & Gunn (1995). The scales of the two vertical axes are chosen in such a way that AGN volume emissivity and SFR density overlap each other.

Figure 2. As Fig. 1, for \( q_0 = 0.15 \) (SFR densities on the left-hand y-axis, AGN volume emissivities on the right-hand y-axis). Small filled circles at \( z \leq 1.2 \) show the galaxy SFR transformed from \( q_0 = 0.5 \) to 0.15 by correcting luminosities and volumes within each redshift interval (correction factors being 1, 0.9, 1.15, 1.21 and 1.27 for data bins ranging from \( z = 0 \) to 1.2).

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the merging picture of elliptical and S0 galaxy formation (e.g. Toomre & Toomre 1972; Barnes & Hernquist 1992), an accelerated star formation history in high-density environments is naturally accounted for by a higher rate of galaxy interactions and mergers at early epochs.

3 FORMATION AND EVOLUTION OF AGN

Quasars and AGN have been studied in all accessible wavebands, in all of them showing evidence for strong cosmological evolution. The most efficient AGN selection comes from X-ray surveys: a purely flux-limited sample at X-ray energies above 0.5 keV contains a vast majority of AGN with no particular bias as a function of redshift. The same is not true for optical searches, where a function of redshift. The same is not true for optical searches, where a function of redshift. The same is not true for optical searches, where various kinds of evolution patterns have been tested, including pure density evolution (PDE), pure luminosity evolution (PLE) and luminosity-dependent density evolution (LDDE). These X-ray surveys indicate for the first time that the AGN evolution is consistent with strict number density conservation (PLE), and rather requires a combined increase with redshift of the source number and luminosity (LDDE).

The X-ray luminosity function \(n(L_x,z)\) (sources per unit volume and unit logarithmic \(L_x\) interval) is modelled by Miyaji et al. as a two-power-law expression:

\[
n(L_x,z) \propto \left(\frac{L_x}{L_{x0}}\right)^{\gamma_1} + \left(\frac{L_x}{L_{x1}}\right)^{\gamma_2}^{-1} n(L_x,z),
\]

where \(L_x\) is the luminosity in the 0.5–2 keV band, \(n(L_x,z)\) is the luminosity-dependent evolution term, and \(\gamma_1 = 0.6, \gamma_2 = 2.3\). The best-fitting LDDE model implies a lower evolution rate at lower \(L_x\), and simple density evolution (PDE) for the higher luminosity sources: \(n(L_x, z) = (1+z)^p\), where \(p\) linearly increases with \(\log L_x\) for \(L_x \leq 10^{44.45}\) erg s\(^{-1}\) and is \(\approx 5.5\) above. The number density of high-\(L_x\) QSOs as a function of \(z\) has been used by Hasinger (1998) to estimate the evolution of the AGN emissivity.

We report in Table 1 and in Figs 1 and 2 (as large filled squares) estimates of the soft X-ray emissivity per comoving volume versus \(z\) for AGN more luminous than \(L_{\text{d}} = 10^{44.25}\) erg s\(^{-1}\) (this is the luminosity threshold above which a pure density evolution applies). It is apparent in these plots that there is a remarkable similarity in the \(z\)-dependences of the emissivity of high-luminosity AGN and the SFR history of elliptical/S0 galaxies (hatched areas). Both functions imply a faster decrease with cosmic time of the emissivity with respect to that of the general field population. A very steeply declining emissivity of luminous AGN is also confirmed by the fast evolution of optical quasars (thick dashed lines).

Table 1. Luminosity density \(L_d\) between 0.5 and 2 keV per comoving volume in erg s\(^{-1}\) Mpc\(^{-3}\) of AGN with \(\log L > \log L_d = 44.25\). Note that, for any values of \(\log L_d > 44\), \(L_d\) scales in proportion to \((\log L_d/10^{44.25})^{1.5}\).

| \(z_{\text{min}}\) | \(z_{\text{max}}\) | \(L_d\) | \(q_0 = 0.5\) | \(L_d\) | \(q_0 = 0.15\) |
|------------------|------------------|--------|-------------|--------|---------------|
| 0.05             | 0.20             | 1.71x10\(^{37}\) | 3.20x10\(^{36}\) | 1.68x10\(^{37}\) | 3.08x10\(^{36}\) |
| 0.20             | 0.40             | 3.24x10\(^{37}\) | 6.02x10\(^{36}\) | 3.15x10\(^{37}\) | 5.66x10\(^{36}\) |
| 0.40             | 0.75             | 5.95x10\(^{37}\) | 1.33x10\(^{37}\) | 6.39x10\(^{37}\) | 1.33x10\(^{37}\) |
| 0.75             | 1.20             | 2.85x10\(^{38}\) | 5.58x10\(^{37}\) | 3.23x10\(^{38}\) | 5.39x10\(^{37}\) |
| 1.20             | 1.50             | 9.52x10\(^{38}\) | 1.87x10\(^{38}\) | 1.09x10\(^{39}\) | 2.02x10\(^{38}\) |
| 1.50             | 2.00             | 1.10x10\(^{39}\) | 2.60x10\(^{38}\) | 1.71x10\(^{39}\) | 3.18x10\(^{38}\) |
| 2.00             | 3.00             | 2.01x10\(^{39}\) | 4.62x10\(^{38}\) | 2.13x10\(^{39}\) | 4.43x10\(^{38}\) |
| 3.00             | 4.00             | 1.52x10\(^{39}\) | 6.79x10\(^{38}\) | 2.27x10\(^{39}\) | 8.56x10\(^{38}\) |

This result is in agreement with the local evidence for an association between nuclear supermassive dark objects and massive spheroids, and with the identification of the hosts of luminous quasars as galaxies with an early-type morphology.

On the other hand, a direct comparison with the population emissivities of lower luminosity AGN is difficult, as the present sensitivity limits prevent measurement of the luminosity function of very faint AGN. Here the information from the XRB becomes essential. Adopting the LDDE best-fitting model as a description of the luminosity function of medium- to high-luminosity AGN, we have extrapolated it to lower \(L_x\) in such a way to reproduce most of the observed low-energy XRB. The top two continuous lines in Figs 1 and 2 are the AGN 0.5–2 keV luminosity density as a function of \(z\) corresponding to such two extrapolations, one producing 60 per cent (henceforth LDDE1) and the other 90 per cent (LDDE2) of the XRB at 1 keV.

We see an accurate match between the redshift dependences of the global AGN emissivity and of the rate of formation of stars in the field galaxy population at \(z \leq 1.2\). At \(z \geq 1.5\), X-ray observations indicate that the AGN emissivity stays constant, roughly as has been found for the SFR density. Then, within the uncertainties, the close association of galaxy and AGN evolution may hold over a substantial redshift interval.

How significant is the difference in the evolution rates between AGN of high and low X-ray luminosity? Assuming a luminosity threshold at \(L_{\text{d}} = 10^{44.25}\) erg s\(^{-1}\), we find the following:

(i) the LDDE1 \(q_0 = 0.15\) model implies an increase in the volume emissivity going from \(z = 0\) to 1.5 by a factor of 100 for sources with \(L > L_{\text{d}}\) and by a factor of 10 for sources with \(L < L_{\text{d}}\); in the \(q_0 = 0.5\) case, the two factors become 100 and 16;

(ii) for the LDDE2 \(q_0 = 0.15\) model, the evolution in the volume emissivity is by factors of 100 for \(L > L_{\text{d}}\) and 30 for \(L < L_{\text{d}}\), while for \(q_0 = 0.5\) the two factors become 100 and 50.

Altogether, there is at least a factor of 2 difference in the evolution rates of high-\(L_x\) and low-\(L_x\) AGN, and this factor may get as high as 10 for the open LDDE1 case.

4 DISCUSSION

The similarities in the evolution rates between high-luminosity AGN and massive spheroidal galaxies, as well as those between low-luminosity AGN and the field galaxy population, call for a close relationship between the processes triggering star formation and those responsible for the gas flow fueling the massive black hole. If the star formation and black hole accretion processes were really concomitant, we would expect the luminosity functions of...
starbursting galaxies and those of quasars and AGN to have similar shapes and perhaps similar normalizations when the luminosities are expressed in bolometric units. This indeed seems indicated by comparative study of the bolometric luminosity functions of luminous far-infrared galaxies (the far-infrared flux being a good measure of the SFR), of bright optical quasars (Schmidt & Green 1983), and of lower luminosity Markarian Seyferts, as reported by Soifer et al. (1987) and Sanders & Mirabel (1996): these luminosity functions have been found to share not only very similar power-law shapes at high luminosities \( [\ln(L_{\text{bol}}) \sim L^{-2.1}] \), but also similar (within a factor of \( \sim 2 \)) normalizations.

We interpret this coincidence as a further support for our results.

### 4.1 The energetics associated with star formation and AGN activity

Although substantial uncertainties are inherent in the absolute normalization of various curves in Figs 1 and 2, it may be worth making an order-of-magnitude comparison of the energetics associated with the processes of stellar formation in galaxies and black hole accretion in AGN. Interesting constraints will ensue from matching them with the local remnants (i.e. low-mass stars and supermassive black holes) of past activities.

Let us first evaluate the global bolometric emissivity due to AGN as a function of \( z \) by applying a bolometric correction to the 0.5–2 keV emissivity (the top two lines in the figures). From the average X-ray to optical spectral index \( \alpha_{\text{ox}} = \log(L_{2500}/L_{\text{2 keV}})/2.605 = 1.4 \) (La Franca et al. 1995) we obtain the 2500-Å flux, and then correct it by a further factor of 5.6 to get the bolometric flux (Elvis et al. 1994). For type 1 AGN (dominating the soft X-ray samples) we then find \( L_{\text{BOL, type 1}} = 50 L_{0.5-2 \text{ keV}} \). Since type 1 AGN contribute only \( \sim 20 \text{ per cent} \) to the total hard X-ray background (e.g. Schmidt & Green 1983), we have another factor of \( \sim 5 \) to account for the contribution of type 2 AGN to the global emissivity:

\[
L_{\text{BOL,AGN}} \sim 5 L_{\text{BOL, type 1}} \sim 250 \left( \frac{f_{\text{BOL}}}{250} \right) L_{0.5-2 \text{ keV}},
\]

where \( f_{\text{BOL}} \) parametrizes the average bolometric correction factor to the 0.5–2 keV flux.

As for galaxies, the scaling factor from \( \dot{M} \) (\( \text{M}_\odot \text{ yr}^{-1} \)) to bolometric luminosity is simply given by

\[
L_{\text{BOL, SFR}}(\text{erg s}^{-1}) = c^2 eM \sim 6 \times 10^{43} \frac{\dot{M}}{0.001 \text{ (M}_\odot \text{ yr}^{-1})},
\]

for a stellar radiative efficiency of \( \epsilon = 0.001 \), consistent with the assumption by Franceschini et al. (1998) and Madau et al. (1996) of a Salpeter initial mass function with a lower mass limit of \( M_{\text{low}} = 0.1 \text{ M}_\odot \) and primordial initial composition (newly born stars are assumed to release most of their energy immediately).

Assuming a fiducial \( \eta = 10 \) per cent radiation efficiency by black hole accretion, and taking into account that there is a factor of \( 2.4 \times 10^{40} \) to make the left-hand axis scale in Figs 1 and 2 coincide with that of the right-hand axis, we find that the ratio of the mass \( M_{\text{BH}} \) of the remnant locked into a supermassive black hole after the AGN phase to the remnant mass in low-mass stars (\( M_\odot \)) should be

\[
M_{\text{BH}} = 0.001 \left( \frac{\epsilon}{0.001} \right) \left( \frac{0.1}{\eta} \right) \left( \frac{f_{\text{BOL}}}{250} \right) M_\odot.
\]

If compared with the locally observed ratio of \( M_{\text{BH}} \) to the mass of the host spheroid

\[
M_{\text{BH}} = (0.002-0.005) M_{\text{spheroid}},
\]

this result is consistent with the fact that nuclear massive black holes are found to be primarily associated with galactic bulges, and not, for example, with the disc components that contribute substantially to \( M_\odot \) in equation (3).

A similar exercise, comparing the low-mass stellar remnants in E/S0s with the black hole remnants of massive/luminous quasars (respectively hatched regions and filled squares in Figs 1 and 2) would involve definition of the X-ray luminosity threshold \( L_{\text{th}} \) above which AGN are hosted by massive spheroidal galaxies, and the ratio of type 2 to type 1 quasars. Assuming, as above, that \( L_{\text{th}} = 10^{44.25} \text{ erg s}^{-1} \) would result in a relation between the black hole mass and the mass of the host spheroid similar to that in equation (3). If we consider that the ratio of type 2 to type 1 objects among luminous quasars is lower than for lower luminosity AGN, then to obtain consistency with the large observed ratio of equation (4) would require (i) a very low radiative efficiency in AGN (\( \eta < 0.1 \), for example, owing to a violent super-Eddington accretion phase), or (ii) a higher bolometric correction for AGN, \( f_{\text{BOL}} > 250 \) (e.g. because of a heavily dust-extinguished phase during quasar formation: Haehnelt et al. 1998; Fabian & Iwasawa 1999), or, finally, (iii) a very high (\( \epsilon > 0.001 \)) radiative efficiency of stars in spheroidal galaxies, as allowed by top-heavy stellar initial mass functions [e.g. for \( M_{\text{low}} = 8 \text{ M}_\odot \), \( \epsilon \) in equation (3) would increase to \( \sim 0.006 \)]. Note that lowering the value of \( L_{\text{th}} \), while improving the match of the predicted black hole mass in equation (3) with the observation in equation (4), would also spoil unacceptably the match between the evolution rates of QSOs and galaxies in Figs 1 and 2; hence it is not a solution.

### 4.2 Quasars and models of structure formation

We have discussed evidence that luminous quasars, associated with massive black holes in massive spheroidal galaxies, evolve on a shorter cosmic time-scale than lower luminosity, lower mass objects. This result does not seem to fit into simple predictions based on the gravitationally driven Press–Schechter formalism. For example Haiman & Menou (1998) obtain from the Press–Schechter theory a much faster decay with cosmic time of the AGN accretion rate (hence of the AGN luminosity) for low-mass black holes in low-mass dark matter haloes, while that of massive objects is expected barely to decrease from \( z = 3 \) to 0. In fact, quite the opposite trend is indicated by our analysis in the previous sections. A similar problem probably arises when explaining with a process of purely gravitational clustering the origin of galaxies, and of their spheroidal components in particular.

What is the trigger and the dominant mechanism for generating a galaxy spheroid together with a supermassive collapsed remnant including \( \sim 0.2 \) per cent of the mass of the host? As discussed by many authors (Kormendy & Sanders 1992; Barnes & Hernquist 1992), the dominant effect is in the gas/stellar dynamical processes related to galaxy interactions and mergers. This is probably the only way to achieve stellar systems with very high central concentrations as observed in early-type galaxies, an obviously favourable birthplace for massive nuclear star clusters and a supermassive collapsed object.

The merging/interaction concept, together with the progressive...
exhaustion of the fuel, allows us to understand the ‘accelerated’ evolution of luminous AGN (Cavaliere & Vittorini 1998), but also the fast decay with time of the star formation in massive spheroidal galaxies. In cosmic environments with higher-than-average density, the forming galaxies have already experienced a high rate of interactions at high redshifts (z > 1), this leading quickly to a population of spheroid-dominated galaxies (observable at low z mostly in groups and clusters of galaxies) containing a massive black hole the accretion history of which is the same as that of the host galaxy. In lower density environments the interaction rate is lower, and the mass locked in the bulge is lower in proportion, with respect to the mass forming stars quiescently in a disc. Galaxies in these low-density environments keep forming stars and accreting matter on to the black hole until the present epoch, and form the low-redshift AGN population.

5 CONCLUSIONS

We have found a close match between the evolution rates of the star formation in galaxies and of the volume emissivity in AGN. This similarity seems to hold not only for high-luminosity AGN (L_x > 10^{44.25} erg s^{-1}) compared with the star formation in massive spheroidal galaxies, but also when comparing the average properties of the global populations, including low-mass/luminosity systems. A correlation of star formation and AGN/quasar activity is also locally indicated by the near-coincidence of the bolometric luminosity functions of luminous star-forming infrared galaxies with those of optical quasars and Markarian Seyferts. Then the same processes as trigger the formation of stars also make a fraction of the gas available to accrete and fuel the AGN. These processes are likely to be the interaction and merging events between gas-rich systems (Barnes & Hernquist 1992; Cavaliere & Vittorini 1998).

Assuming standard energy production efficiencies for black hole accretion and star formation, we have found rough agreement between the volume emissivities of distant quasars and star-forming galaxies and the observed ratios of low-mass stellar and supermassive black hole remnants in local objects.

Finally, we have compared our finding that high-mass/luminosity systems evolve on a shorter cosmic time-scale than lower mass ones with predictions from structure formation theories based on the gravitational clustering and coalescence of dark matter haloes. Altogether, if the latter provide the required background conditions for the development of structures, much more physics is needed – in terms of gas/stellar dynamical processes related to galaxy interactions, and in terms of the progressive exhaustion of the baryonic fuel available and of feedback reaction – to explain observations of AGN evolution and (spheroidal) galaxy formation.

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REFERENCES

Appenzeller I. et al., 1998, ApJS, 117, 319
Barnes J. E., Hernquist L., 1992, Nat, 360, 715
Cavaliere A., Padovani P., 1989, ApJ, 340, L5
Cavaliere A., Vittorini V., 1998, in D’Odorico S., Fontana A., Giallongo E., eds, ASP Conf. Ser. Vol. 146, The Young Universe: Galaxy Formation and Evolution at Intermediate and High Redshift. Astron. Soc. Pac., San Francisco, p. 26
Elvis M. et al., 1994, ApJS, 95, 1
Fabian A. C., Iwasawa K., 1999, MNRAS, 303, L34
Faber S. M. et al., 1997, AJ, 114, 1771
Franceschini A., Silva L., Fasano G., Granato G. L., Bressan A., Arnouts S., Danese L., 1998, ApJ, 506, 600
Hasinger G., 1998, Astron. Nachr., 319, 37
Hasinger G., Burg R., Giacconi R., Schmidt M., Trumper J., Zamorani G., 1998, A&A, 329, 482
Kormendy J., Richstone D., 1995, ARA&A, 33, 581
Kormendy J., Sanders D. B., 1992, ApJ, 390, L53
La Franca F., Franceschini A., Cristiani S., Vio R., 1995, A&A, 299, 19
Lilly S. J., Le Fevre O., Hammer F., Crampton D., 1996, ApJ, 460, L1
McLure R. J., Kukula M. J., Dunlop J. S., Baum S. A., O’Dea C. P., Hughes D. H., 1999, MNRAS, 308, 377
Madau P., Ferguson H. C., Dickinson M. E., Giavalisco M., Steidel C. C., Fruchter A., 1996, MNRAS, 283, 1388
Magorrian J. et al., 1998, AJ, 115, 2285
Meurer G. R., Heckman T. M., Calzetti D., 1999, ApJ, 521, 64
Miyaji T., Hasinger G., Schmidt M., 1999, A&A, submitted
Sanders D., Mirabel F., 1996, ARA&A, 34, 749
Schmidt M., Green R., 1983, ApJ, 269, 352
Schmidt M., Schneider D. P., Gunn J. E., 1995, AJ, 110, 68
Soifer B. T., Sanders D. B., Neugebauer G., Danielson G. E., Lonsdale C. J., Rice W. L., 1989, ApJ, 322, 238
Stanford S., Eisenhardt P., Dickinson M., 1998, ApJ, 492, 461
Steidel C., Dickinson M., Persson S. E., 1994, ApJ, 437, L75
Toomre A., Toomre J., 1972, AJ, 77, 83

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