# The role of starbursts in the formation of galaxies and active galactic nuclei

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# The role of starbursts in the formation of galaxies and active galactic nuclei

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Starbursts are episodes of intense star formation in the central regions of galaxies, and are the sites of *ca.* 25% of the high-mass star formation in the local Universe. In this contribution, I review the role that starbursts play in the formation and evolution of galaxies, the intergalactic medium (IGM), and active galactic nuclei. First, I point out the empirical similarities between local starbursts and the Lyman-break population at high redshift, and emphasize the implied similarities in their basic physical, dynamical and chemical properties. In the local Universe, more-massive galaxies host more-luminous, more-metal-rich, and dustier (IR-dominated) starbursts. This underscores the need for a pan-chromatic approach to documenting and understanding the cosmic history of star formation. Second, I review the systematic properties of starburst-driven galactic superwinds. These drive metal-rich *dusty* gas outward at a typical velocity of 400–800 km $s^{-1}$ (independent of the galaxy rotation speed) and at several times the star-formation rate. They can be directly observed both in local starbursts and high-redshift galaxies. They are probably responsible for establishing the strong mass–metallicity relation in spheroids, and for the metal-enrichment and (pre)heating of the IGM. They *may* have also ejected cosmologically significant amounts of intergalactic dust. Third, I discuss UV observations of the nuclei of type 2 Seyfert galaxies. These show that compact (on a scale of a few hundred pc) heavily reddened starbursts are the source of most of the 'featureless continuum' in UV-bright Seyfert 2 nuclei, and are an energetically significant component in these objects. Finally, I discuss the evolution of the host galaxies of radio-quiet quasars. Rest-frame optical images imply that the hosts at $z \sim 2$ are only as luminous as present-day $L_*$ galaxies, less massive than the hosts of similarly luminous low-$z$ quasars, similar to the Lyman-break galaxies, and much less luminous than powerful radio galaxies at the same redshift. These results are consistent with the idea of hierarchical galaxy assembly, and suggest that super-massive black holes may be formed/fed before their host galaxy is fully assembled.

**Keywords: starbursts; galactic winds; Seyfert galaxies; quasars**

## 1. Introduction

Starbursts are short-lived episodes of intense star formation that usually occur in the 'circum-nuclear' (kpc scale) regions of galaxies, and dominate the integrated emission from the 'host' galaxy (Leitherer *et al.* 1991). Starbursts are major components of the local Universe (see, for example, Gallego *et al.* 1995; Soifer *et al.* 1987), and are the sites of *ca.* 25% of the total (high-mass) star formation in the local Universe (Heckman 1997).

The cosmological relevance of starbursts has been dramatically underscored by the spectacular discovery of populations of high-redshift ($z > 2$) star-forming field galaxies selected by their rest-frame UV continuum emission (Steidel *et al.* 1999; Lowenthal *et al.* 1997), rest-frame far-infrared emission (see, for example, Hughes *et al.* 1998; Barger *et al.* 1999; Cowie, this issue), Ly$\alpha$ emission (Hu *et al.* 1998), and H$\alpha$ emission (Teplitz *et al.* 1998; Mannucci *et al.* 1998). The comoving space density and luminosity of these galaxies imply that they almost certainly represent precursors of typical present-day galaxies and are responsible for the production of a significant fraction of the stars and heavy elements in the present-day Universe (see, for example, Madau *et al.* 1996; Blain *et al.* 1998; Calzetti & Heckman 1999).

Starbursts may also play a vital energetic or evolutionary role in active galactic nuclei (AGN). There have been recurring suggestions to this effect in the Seyfert-galaxy phenomenon (see, for example, Weedman 1983; Perry & Dyson 1985; Terlevich & Melnick 1998; Norman & Scoville 1988; Cid Fernandes & Terlevich 1995). On a more global scale, the rough proportionality between the mass of a super-massive black hole and that of the stellar spheroid in which it now resides (Magorrian *et al.* 1998; Van der Marel 1999) strongly suggests that the quasar phenomenon is an intimate part of the formation or early evolution of massive ellipticals and bulges.

In this contribution, I will therefore discuss the relevance of local starbursts to understanding the high-redshift Universe and its major baryonic components: star-forming galaxies, AGN and the intergalactic medium (IGM). In § 2 I will argue that starbursts are the only local analogues to the star-forming galaxies observed at high redshift, and will summarize some of the inferences that follow. In § 3 I will describe the systematic properties of starburst-driven galactic superwinds and summarize the cosmological implications of these outflows. In § 4 I will present a status report on efforts to understand the energetic/evolutionary significance of young stars in/near the nuclei of Seyfert galaxies. Then, in § 5 I will report new results on the properties of the host galaxies of high-redshift radio-quiet quasars, and compare these with theoretical expectations.

## 2. Starbursts as analogues to high-$z$ galaxies

Starburst galaxies are the only plausible local analogues to the population of star-forming galaxies at high redshift. Meurer *et al.* (1997) showed that local starbursts and high-redshift Lyman-break galaxies (LBGs) have similar rest-frame UV surface brightnesses and UV colours. Using the empirical correlation between UV colour and extinction for local starbursts, the implied bolometric surface brightnesses of the high-$z$ galaxies are, thus, also very similar to local starbursts: typically *ca.* $10^{10}$–$10^{11} L_{\odot}\ \mathrm{kpc}^{-2}$. The high-redshift LBGs appear to be 'scaled-up' (larger and more-luminous) versions of local starbursts. The intrinsic UV surface brightnesses are roughly three orders of magnitude higher than the discs of normal spirals, and indeed normal spirals at $z \sim 3$ (if they exist) would be virtually undetectable in Hubble Space Telescope (HST) rest-UV images due to their low surface brightness (see, for example, Hibbard & Vacca 1997; Lanzetta *et al.* 1999).

The similarity in the surface brightnesses of local starbursts and LBGs immediately implies that there are also strong similarities in their basic physical properties. A high

UV surface brightness implies a high star-formation rate (SFR) per unit area ($\Sigma_{\mathrm{SFR}}$), and, thus, high surface mass densities in the stars ($\Sigma_*$) and in the interstellar gas ($\Sigma_{\mathrm{g}}$) that fuels the star formation. A typical case would have $\Sigma_{\mathrm{SFR}} \sim 10 M_\odot\ \mathrm{yr}^{-1}\ \mathrm{kpc}^{-2}$ and $\Sigma_{\mathrm{g}} \sim \Sigma_* \sim 10^9 M_\odot\ \mathrm{kpc}^{-2}$. These are roughly $10^3$ ($\Sigma_{\mathrm{SFR}}$), $10^2$ ($\Sigma_{\mathrm{g}}$) and $10^1$ ($\Sigma_*$) times larger than the corresponding values in the discs of normal galaxies.

The basic physical and dynamical properties of starbursts and the Lyman-break objects follow directly from the above. A gas surface mass density of $10^9 M_\odot\ \mathrm{kpc}^{-2}$ corresponds to an extinction of $A_{\mathrm{B}} \sim 10^2$ for a Milky Way dust-to-gas ratio. The characteristic dynamical time in the star-forming region will be short:

$$t_{\mathrm{dyn}} \sim (G\rho)^{-1/2} \sim (G\Sigma_{\mathrm{tot}} H)^{-1/2} \sim \text{a few Myr},$$

where $H \sim 10^2$ pc is the thickness of the disc. A surface brightness of a few $\times 10^{10} L_\odot\ \mathrm{kpc}^{-2}$ corresponds to a radiant energy density inside the star-forming region that is roughly $10^3$ times the value in the interstellar medium (ISM) of the Milky Way. Finally, simple considerations of hydrostatic equilibrium imply correspondingly high total pressures in the ISM: $P \sim G\Sigma_{\mathrm{g}}\Sigma_{\mathrm{tot}} \sim$ a few $\times 10^{-9}\ \mathrm{dyn\,cm}^{-2}$ ($P/k \sim$ a few $\times 10^7\ \mathrm{K\ cm}^{-3}$, or several thousand times the value in the local ISM in the Milky Way). The rate of mechanical energy deposition (supernova heating) per unit volume is also $10^3$ or $10^4$ times higher than in the ISM of our Galaxy.

To summarize, the strong empirical similarity between local starbursts and the high-$z$ LBGs implies strong similarity in their basic physical properties. The conclusion seems inescapable: *if we want to understand the LBGs in the early Universe, we need to understand local starbursts.*

As discussed by Heckman *et al.* (1998), local starbursts occupy a very small fractional volume in the multi-dimensional manifold defined by such fundamental parameters as the extinction, metallicity and vacuum-UV line strengths (both stellar and interstellar) of the starburst and the rotation speed (mass) and absolute magnitude of the starburst's 'host' galaxy. In particular, more-massive galaxies host more-luminous, more-metal-rich and dustier (more-heavily extincted) starbursts. There are simple physical explanations for these trends. Firstly, simple considerations of causality for a self-gravitating system with a gas mass $M_{\mathrm{gas}} = f_{\mathrm{gas}} M_{\mathrm{tot}}$ imply that the maximum possible star-formation rate is given by the conversion of all the gas into stars in one crossing time: $\mathrm{SFR}_{\mathrm{max}} \sim M_{\mathrm{gas}}/t_{\mathrm{dyn}} \sim f_{\mathrm{gas}}\sigma^3/G$. Thus, more-massive galaxies (with larger velocity dispersions $\sigma$) can sustain bursts with higher star-formation rates and, therefore, larger luminosities. The physical basis for the strong observed correlation between galaxy mass and metallicity will be discussed in § 3 below. Finally, the trend for more-metal-rich starbursts to be more-heavily extincted follows, provided that neither the gas-column density towards the starburst nor the fraction of interstellar metals locked into dust grains are strong inverse functions of metallicity.

The result of these correlations is that a UV census of the local Universe would not only underestimate the true star-formation rate, it would also systematically under-represent the most-powerful, most-metal-rich starbursts occurring in the most-massive galaxies. This effect can clearly be seen in the recent comparison of the vacuum-UV and far-IR galaxy luminosity functions at low redshift by Buat & Burgarella (1998). Estimates of star-formation rates at high redshift based on rest-frame vacuum-UV sample selection probably suffer the same bias, and, thus, may under-represent the ultra-luminous progenitors of the most-massive present-day spheroids.

It is tempting to speculate (based on the empirical properties of local starbursts) that the Submillimetre Common User Bolometer Array (SCUBA) far-IR-selected sources at high $z$ may represent just such objects. This speculation is consistent with the relative space densities of the most-luminous LBGs and the SCUBA sources (Meurer *et al*. 1999).

*Clearly, we cannot understand the cosmic evolution of the star-formation rate and the formation and evolution of galaxies without a panchromatic approach.*

## 3. Starburst-driven superwinds

Over the last few years, observations have provided convincing evidence of the existence (and even the ubiquity) of 'superwinds': galactic-scale outflows of gas driven by the collective effect of multiple supernovae and stellar winds in a starburst (see, for example, Lehnert & Heckman 1996; Dahlem *et al*. 1998; Martin 1999).

In this section I will summarize the systematic properties of superwinds as gleaned from the analysis of their X-ray emission and their UV–optical absorption lines. The X-ray data have proven particularly important, since they are the only direct probe of the energetically dominant 'piston' of hot gas that drives the flow. The interstellar absorption lines trace cooler and denser gas that has probably been entrained into the outflowing hot gas (see, for example, Suchkov *et al*. 1994), and supply crucial complementary data. They provide unambiguous information about the magnitude and *sign* of the radial velocities of the gas, more fully sample the whole range of gas densities in the outflow (rather than being strongly weighted in favour of the densest material that may contain relatively little mass), and can be used to study outflows in high-redshift galaxies, where the associated X-ray or optical *emission* may be undetectably faint (Franx *et al*. 1997; Pettini *et al*. 1998).

Martin (1999) empirically quantified the global effects of intense star formation on the ISM by estimating the outflow rates and velocities for a local sample of starburst and related galaxies. I will follow her approach, but update it by adding new X-ray results on additional galaxies and improve upon it by including results from our (Heckman *et al*. 2000) analysis of the interstellar absorption lines in starbursts (a data type not considered by Martin). The principal results are as follows.

*The outflow speeds are, typically,* 400–800 km $\mathrm{s}^{-1}$*, independent of the rotation speed of the 'host' galaxy.* This result is shown in figure 1. Heckman *et al*. (2000) show that the absorbing gas typically spans a velocity range from close to the galaxy systemic velocity up to some maximum blueshift. They argued that this can be understood if the hot outflow is ablating material off of cold dense clouds and then accelerating it up to some terminal velocity. It is these inferred terminal velocities that are plotted in figure 1. In the case of the X-ray data, outflow velocities cannot be observed directly. Instead, we have estimated the outflow speed from the observed gas temperature following Chevalier & Clegg's (1985) solution for an adiabatic wind fed by gas at a temperature $T$: $v \sim (5kT/\mu)^{1/2}$, where $\mu$ is the mean mass per particle. This is a conservative approach as it ignores any kinetic energy that the X-ray-emitting gas may already have. It is encouraging that the overall agreement between the two datasets is satisfactory.

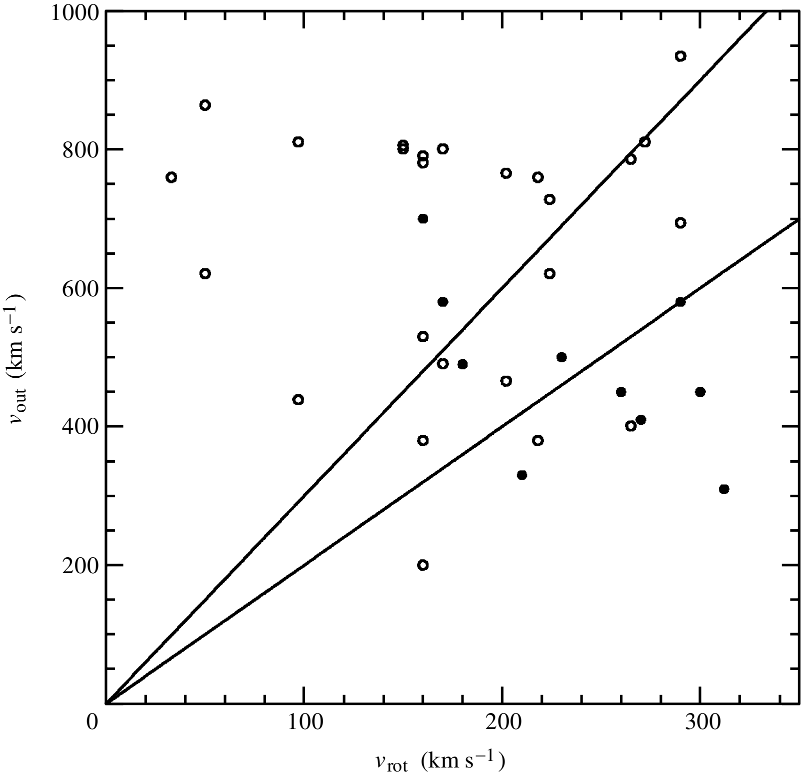

Figure 1. Plot of the galaxy rotation speed versus the inferred terminal velocity of the outflow for starburst galaxies. The two diagonal lines show the relations $v_{\text{out}} = 2v_{\text{rot}}$ and $v_{\text{out}} = 3v_{\text{rot}}$. Data points based on blueshifted interstellar absorption-line profiles are indicated by filled dots and the points based on the X-ray temperatures are indicated by empty dots. Note that the two datasets are consistent with each other, imply that the outflow speed is independent of the host galaxy potential well depth, and, thus, suggest that outflows will preferentially escape from the least-massive galaxies (see Heckman *et al.* (2000) for details).

*The implied outflow rates of metal-enriched material probably exceed the star-formation rate.* I have calculated star-formation rates for a large sample of starburst galaxies for which mass-outflow rates can be estimated from either interstellar absorption lines, X-ray emission, or H$\alpha$ emission-line kinematics. The star-formation rates assume a Salpeter initial mass function extending from 0.3 to 100$M_\odot$. For the outflow rates based on the absorption-line data, I follow Heckman *et al.* (2000) and set these equal to

$$\dot{M} \sim 60 r_* N_{\text{H}} \Delta v (\mathit{\Omega}_{\text{w}}/4\pi) M_\odot \text{ yr}^{-1},$$

where $r_*$ (kpc) is the radius of the region of mass-injection (the starburst), $N_{\text{H}}$ ($3 \times 10^{21}$ cm$^{-2}$) is the total H column density in the absorbing material, $\Delta v$ (200 km s$^{-1}$) is the mean outflow velocity, and $\mathit{\Omega}_{\text{w}}$ is the solid angle filled by the wind. I adopted the values measured or estimated for these parameters by Heckman *et al.* (2000), Lehnert & Heckman (1995) and Armus *et al.* (1990). For the outflow rates derived from the X-ray data, I have simply taken the inferred mass of hot gas (assuming a volume filling factor of unity) and divided it by the outflow time (approximately equal to the sound-crossing time) for the X-ray emitting region. I also include the estimates for the outflow rates in the warm ionized gas from Martin (1999), which are based on the observed velocities in the H$\alpha$-emitting gas and the masses derived by assuming that this gas is in pressure balance with the ram pressure of the superwind (see Martin (1999) for details). While each method is crude, and makes simplifying assumptions that may be unwarranted, it is gratifying that the three methods yield similar results: the median value for $\dot{M}/\mathrm{SFR} = 1.4$ for the absorption-line data, 2.8 for the X-ray data, and 1.6 for the H$\alpha$ data. In fact, since these three methods measure different gas phases, the *total* outflow rate could be approximated as the sum of the three rates. Thus, gas is being expelled from starbursts at a rate in excess of the rate that gas is being processed into stars.

*The implied outflow rates of kinetic/thermal energy are a significant fraction of the total injection rate by supernovae and stellar winds.* The rate at which superwinds carry energy is uncertain. Simple estimates can be made from the X-ray data by calculating the thermal energy content in the hot gas (assuming unit-volume filling factor) and dividing this by the dynamical time for the X-ray-emitting region. As emphasized by Strickland (1998), this ignores the effects of clumping (which will reduce the thermal energy) and of the supersonic flow speeds (which represent significant kinetic energy). Energy (more properly momentum) outflow rates can also be deduced from the radial pressure gradients observed via standard optical emission-line diagnostics, assuming that these trace the sum of the ram and thermal pressure in the outflow (see, for example, Heckman *et al*. 1990; Lehnert & Heckman 1996). Both techniques suggest that the majority of the kinetic/thermal energy supplied by the supernovae and stellar winds is being carried out in the flow (and has not been radiated away). The key seems to be that the porosity of the starburst ISM is high, so that most supernovae detonate in a rarefied preheated medium (see, for example, Heckman *et al*. 1990; Marlowe *et al*. 1995).

*The outflows are apparently quite dusty, with inferred reddenings of* $E(B-V) \sim 1$ *over regions of a few to* 10 kpc *in size.* Heckman *et al*. (2000) mapped the Na-$D$ interstellar absorption line over regions with sizes of a few to 10 kpc in a sample of 18 starbursts. Figure 2 shows the strong correlation that they found between the depth of the absorption-line profile (roughly proportional to the fraction of the emitting region covered by absorbing gas) and the line-of-sight reddening towards the emitting region. The observed reddening is substantial, with $E(B-V) \sim 0.9 \pm 0.4$ (corresponding to $N_{\mathrm{H}} \sim$ several $\times 10^{21}\ \mathrm{cm}^{-2}$ for normal galactic dust). This generalizes Phillips's (1993) discovery of a spectacularly dusty few-kpc-scale outflow in the halo of the starburst galaxy NGC 1808.

The four results above have a variety of important implications. The lack of independence of the outflow speed upon the galaxy rotation speed strongly suggests that the outflows selectively escape the potential wells of the less-massive galaxies, carrying metals with them. This process plausibly accounts for the strong mass–metallicity relation in ellipticals and bulges. Lynden-Bell (1992) has proposed an appealingly simple model in which the fraction of starburst-produced metals that are retained by a galaxy experiencing an outflow is proportional to the galaxy potential-well

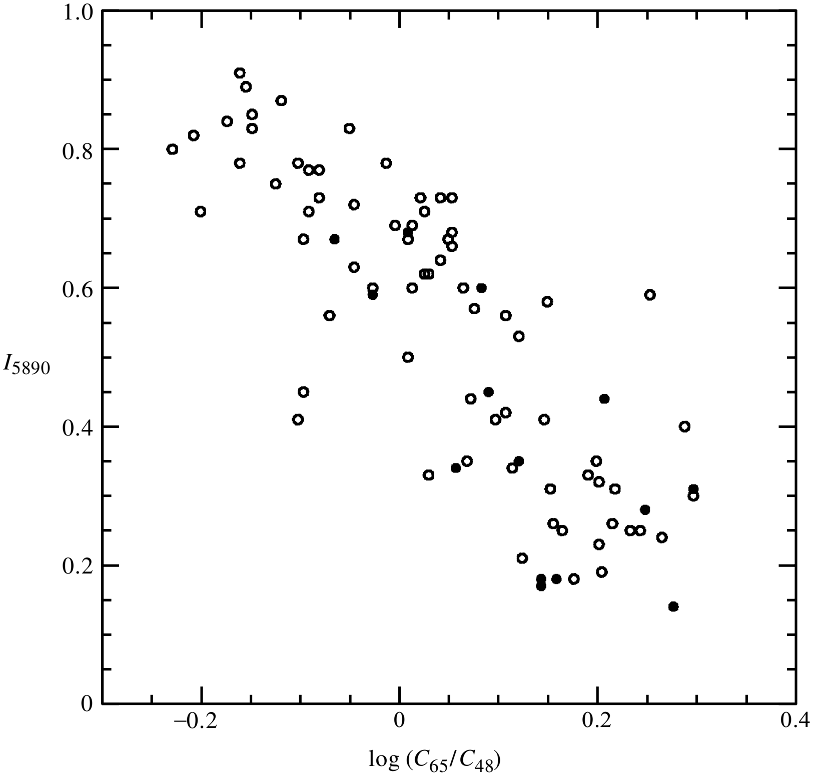

Figure 2. Plot of the normalized residual intensity at the centre of the interstellar NaI$\lambda$5890 transition ($I_{5890}$) versus the log of the colour of the optical continuum (the ratio of the values of $F_\lambda$ at rest wavelengths of 6560 and 4860 Å). Points plotted as filled dots are the nuclei of powerful starbursts. Other points are off-nuclear locations. The deeper the NaI absorption line, the more reddened the background starlight. An unreddened starburst population should have $\log(C_{65}/C_{48}) = -0.3$. For a standard galactic reddening curve, the implied $A_V$ ranges up to roughly four magnitudes for the most-reddened sight lines (see Heckman *et al*. (2000) for details).

depth for galaxies with $v_{esc} < v_{out}$, and asymptotes to full retention for the most-massive galaxies ($v_{esc} > v_{out}$). For $v_{out}$ in the measured range (figure 1), such a simple prescription can reproduce the observed mass–metallicity relation for spheroids (Lynden-Bell 1992).

At the same time, superwinds could deposit the required amount of observed metals in the intracluster medium (see, for example, Gibson *et al*. 1997). The kinetic energy carried out by superwinds at high redshift could be the agent that 'preheated' the proto-intracluster medium prior to the collapse/formation of rich clusters (Ponman *et al*. 1999; Evrard, this issue). If the ratio of ejected metals to stellar spheroid mass is the same globally as in clusters of galaxies, the present-day mass-weighted metallicity of a general IGM with $\Omega_{IGM} = 0.015$ will be approximately one-sixth solar (see also Renzini 1997). These intergalactic metals could reconcile the apparent deficit in the inventory of metals contained by stars in the present Universe compared with the expectations based on the integrated amount of high-mass star formation over cosmic time (see, for example, Aguirre 1999). Pettini (this issue) notes a similar problem with 'missing metals' at high $z$. Highly ionized superwind ejecta may be a plausible place to hide them. Superwinds may also help alleviate the problems in understanding the apparently wide distribution of metals in the Ly$\alpha$ forest (Pettini, this issue; Efstathiou, this issue).

More speculatively, *if* the outflowing dust survives its journey, the cumulative effect of dusty superwinds could lead to a cosmologically significant amount of intergalactic dust ($\Omega_{\rm dust}$ = a few$\times 10^{-5}$), which would seriously affect the Hubble diagram for type Ia supernovae (Aguirre 1999; Aguirre & Haiman 1999). Finally, Kronberg *et al.* (1999) have argued that a substantial fraction of the IGM at high redshift can be permeated with magnetic fields carried out of the first generation of galaxies by early superwinds.

## 4. The starburst–Seyfert connection

There have been many observational investigations into the possible presence of starbursts in Seyfert nuclei, and it is beyond the scope of this contribution to review this literature. Instead, I want to report briefly on efforts by our group to make direct spectroscopic detections of hot, massive stars in a large, unbiased sample of Seyfert nuclei.

According to the standard 'unified' picture for radio-quiet AGN, the principal building blocks for a Seyfert nucleus are as follows.

(1) A super-massive black hole and its associated accretion disc (the primary source of X-ray-through-optical continuum emission).

(2) An optically and geometrically thick circum-nuclear torus of dust and gas, with an inner radius of a few pc and an ill-defined outer radius (of order $10^2$ pc). It is viewed close to its equatorial plane (polar axis) in type 2 (type 1) Seyferts.

(3) A 'mirror' of dust and/or warm electrons located along the polar axis of the torus.

Thus, the optimal targets in which to search for hot stars are the type 2 Seyfert nuclei, in which the torus providentially blocks out the blinding glare from a hidden type 1 Seyfert nucleus. Indeed, type 2 Seyfert nuclei have long been known to exhibit a 'featureless continuum' (FC) that produces most of the UV light and, typically, 10–30% of the visible/NIR light (the rest appears to be light from an ordinary old population of stars). Until recently, it was thought that the optical/UV FC was mostly light from the hidden type 1 Seyfert nucleus that had been reflected into our line of sight by the mirror.

Instead, if at least part of the FC is produced by a population of hot stars, it should not actually be featureless! Instead, spectroscopy in the blue and near-UV should show the high-order Balmer lines in absorption (unlike H$\alpha$ and H$\beta$, which are dominated by nebular emission) and weak HeI stellar photospheric lines (Gonzalez-Delgado *et al.* 1999). Spectra in the vacuum-UV should reveal strong stellar wind lines and weaker stellar photospheric lines (cf. De Mello *et al.* 1999). To test this possibility we have therefore undertaken a programme to obtain high-resolution vacuum-UV images and spectra (with HST) and near-UV spectra (with ground-based telescopes) of a representative sample of the brightest type 2 Seyfert nuclei.

The first results have been presented in detail in Heckman *et al*. (1997) and Gonzalez-Delgado *et al*. (1998). HST imaging shows that the UV continuum source in every case is spatially resolved (with a scale size of a few hundred pc or greater). In some cases, the morphology is strikingly reminiscent of UV images of starbursts. In other cases, a component of the UV continuum is roughly aligned with the inferred polar axis of the obscuring torus (as expected for reflected and/or reprocessed light from the central engine).

Of the original sample of 13 type 2 Seyferts with HST vacuum-UV images, only four were bright enough for us to obtain spectra of adequate quality in the crucial UV spectral window from *ca.* 1200 to 1600 Å. However, these spectra are decisive: all four show the clear spectroscopic signature of a starburst population that dominates the UV continuum. In addition to classic, strong, stellar wind features (NV$\lambda$1240, SiIV$\lambda$1400 and CIV$\lambda$1550), we can also detect weaker and much narrower absorption features from highly excited transitions (which are, therefore, indisputably of stellar origin).

In each of the four cases, if we use the empirical 'starburst attenuation law' (Calzetti *et al*. 1994; Meurer *et al*. 1999) to correct the observed UV continuum for dust extinction, we find that the bolometric luminosity of the nuclear ($10^2$ pc-scale) starburst is comparable with the estimated bolometric luminosity of the 'hidden' type 1 Seyfert nucleus (of the order of $10^{10} L_\odot$). Large-aperture UV spectra with internal ultraviolet explore (IUE) imply the existence of a surrounding larger-scale (few kpc) and more powerful (a few × $10^{10}$–$10^{11} L_\odot$) dusty starburst that is energetically capable of powering the bulk of the observed far-IR emission from the galaxy. Thus, starbursts are an energetically significant (or even dominant) component of at least *some* Seyfert galaxies.

However, we have HST spectra of only four type 2 Seyferts, and these are strongly biased in favour of cases with high UV surface brightness. Can we say anything more general? To address this, we have embarked on a programme to obtain spectra from *ca.* 3500 to 9000 Å of a complete sample of the 25 brightest type 2 Seyfert nuclei in the local Universe. These objects are selected from extensive lists of known Seyfert galaxies on the basis of the flux of either the nebular line emission from the 'narrow line region' (the [OIII]$\lambda$5007 line) or from the nuclear radio source (Whittle 1992).

We are still analysing these spectra, but even a cursory inspection of the near-UV region (below 4000 Å) shows that about half have pronounced Balmer absorption lines, whose strength is consistent with a population of late O or early B stars. In several cases we can also detect those photospheric HeI absorption lines ($\lambda$4921, $\lambda$4387, $\lambda$3819) that are not filled in by nebular emission. In most of the remainder of the sample, the FC is so weak relative to the light from a normal old-bulge stellar population that its origin is still not clear. Recent work in a related vein has been undertaken by Cid Fernandes *et al*. (1998) and Schmitt *et al*. (1999). Their results agree, at least qualitatively, with ours: they find that most of the optical and near-UV FC in type 2 Seyfert nuclei is produced by young and intermediate-age stars (age less than or equal to 100 Myr).

Thus, it is clear that massive stars and starbursts play an important energetic role in a significant fraction of Seyfert nuclei. What is not yet clear is whether starbursts are an *essential* component of the Seyfert phenomenon and what (if any) the causal or evolutionary connection might be. Perhaps, as Cid Fernandes & Terlevich (1995) suggested, the starburst is an inevitable by-product of the dense molecular torus that is now believed to be a fundamental part of the inner machinery of AGN (both obscuring the 'central engine' and serving as its fuel source). If true, this would have major implications for the relationship between quasars and galaxy formation.

## 5. The host galaxies of high-$z$ radio-quiet quasars

The cosmic evolution of the population of powerful radio galaxies has been well documented over the past decade (see Rottgering *et al*. 1999). The uniformity of the $K$-band Hubble diagram out to $z \sim 4$ and the evolution of the red envelope in the visible and near-IR colours are consistent with a large redshift of formation and the subsequent passive evolution of the progenitors of (some) present-day giant elliptical galaxies (see, for example, Lilly 1989; Eales & Rawlings 1996; McCarthy 1999). Much less is known about the evolution of the population of the hosts of radio-loud quasars, but the available data paint a broadly similar picture (see, for example, Lehnert *et al*. 1992; Ridgway & Stockton 1997; McLure *et al*. 1999). This is consistent with the standard 'unified model' in which radio-loud quasars and radio galaxies are drawn from the same parent population, but the quasars (radio galaxies) are viewed roughly along (perpendicular to) the polar axis of a dusty torus (Barthel 1989).

While the notion of the 'monolithic' formation of apparently massive elliptical galaxies at high redshifts does not fit comfortably into the standard cold-dark-matter picture of hierarchical assembly at late times, powerful radio galaxies are exceedingly rare objects. For $H_0 = 50\ \mathrm{km\ s^{-1}\ Mpc^{-1}}$ and $\Omega = 1$, 3CR radio galaxies at $z = 2.5$ have a comoving space density of only $0.2\ \mathrm{Gpc^{-3}}\ \Delta \log P_{\mathrm{rad}}^{-1}$, while the fainter 6C (Eales 1999) and MRC (McCarthy 1999) radio galaxies have space densities roughly $10^2$ times larger (Dunlop & Peacock 1990). These values can be compared with the present-day space density of first-ranked-cluster galaxies (roughly $5000\ \mathrm{Gpc^{-3}}$; see Bahcall & Cen 1993). Even allowing for a short lifetime for the radio galaxy phase, the evolved descendants of *powerful* radio galaxies would account for only a small minority of the first-ranked-cluster elliptical galaxies.

In contrast, radio-quiet quasars are far more common and, therefore, more likely to be progenitors of typical present-day early-type galaxies. Radio-quiet quasars with $M_{\mathrm{B}} \leqslant -23$ have comoving space densities at $z \sim 2$ of *ca.* $2 \times 10^4\ \mathrm{Gpc^{-3}}$ (Hartwick & Schade 1990). Now, for a quasar lifetime of the order of the Eddington growth time (a few per cent of the Hubble time at $z = 2$), the implied space density of the present-day descendants is of the order of $10^6\ \mathrm{Gpc^{-3}}$, which is comparable with the space density of $L_*$ Es and S0s (see, for example, Fukugita *et al*. 1998). This identification is quite consistent with the correlation between the masses of super-massive black holes and the spheroids in which they live today. A quasar with $M_{\mathrm{B}} = -24$ powered by accretion at the Eddington rate requires $M_{\mathrm{SMBH}} \sim 2 \times 10^8 M_\odot$, and this super-massive black hole would live today in a spheroid with a mass of $M_{\mathrm{sph},z=0} \sim 5 \times 10^{10} M_\odot$ and $V$-band luminosity of *ca.* $1.5 \times 10^{10} L_\odot \sim 0.4 L_*$ (Magorrian *et al*. 1998; Van der Marel 1999).

Thus, it is clearly important to document the properties of the host galaxies of radio-quiet quasars over a broad range in redshifts. At low redshifts, the hosts of the *most luminous* radio-loud quasars, radio-quiet quasars and radio galaxies all appear to be similar: several-$L_*$ E or S0 galaxies (McLure *et al*. 1999). However,

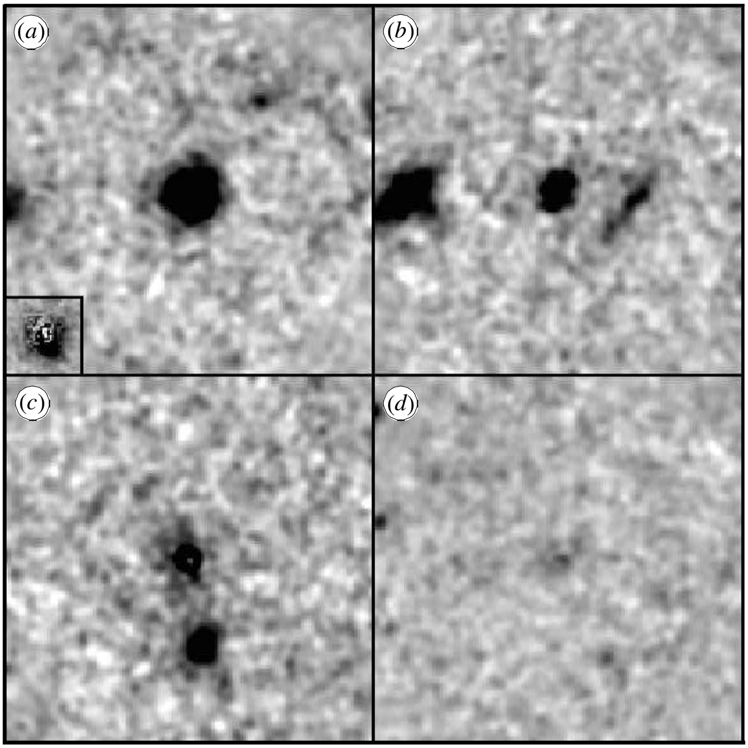

Figure 3. High-$z$ radio-quiet quasar hosts, after the quasar has been subtracted and the image smoothed with a Gaussian kernel of 0.06 arcsec. Each panel has an area of 5.7 arcsec$^2$ (or *ca.* 45 kpc), N up, E left. (*a*) MZZ 9592, $z \sim 2.7$, with an inset of the central region (unsmoothed). There is an off-centre residual host component. (*b*) MZZ 9744, $z \sim 1.8$, (*c*) MZZ 1558, $z \sim 2.7$, (*d*) MZZ 4935, $z \sim 1.8$, host marginally detected. Note the apparent close (*ca.* 10 kpc) companion galaxies in panels (*b*) and (*c*) (see Ridgway *et al.* (1999) for details).

ground-based near-IR imaging of small samples has already hinted that the situation might be quite different at high redshift, with the hosts of radio-quiet quasars being significantly fainter than their radio-loud cousins (Lowenthal *et al.* 1995; but see also Aretxaga *et al.* (1998)).

Recent analyses of HST NICMOS† images of radio-quiet quasars at $z \sim 2$ have now clarified the situation. We (Ridgway *et al.* 1999) have imaged five faint ($M_{\mathrm{B}} \sim -23$) radio-quiet quasars, complementing the analysis reported by Rix *et al.* (1999) of six luminous ($M_{\mathrm{B}} \sim -26$) gravitationally lensed cases. Some examples of the underlying hosts' galaxies in the Ridgway *et al.* (1999) sample are shown in figure 3.

While the samples are still modest in size, several conclusions can already be drawn (see figure 4; Ridgway *et al.* 1999; Rix *et al.* 1999).

(1) Typical radio-quiet quasars at $z \sim 2$ are hosted by galaxies with rest-frame absolute visual magnitudes similar to present-day $L_*$ galaxies ($M_{\mathrm{V}} = -20$ to $-23 = M_{*,\mathrm{V}} \pm 1.5$ mag).

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† Near Infrared Camera and Multi-Object Spectrograph.

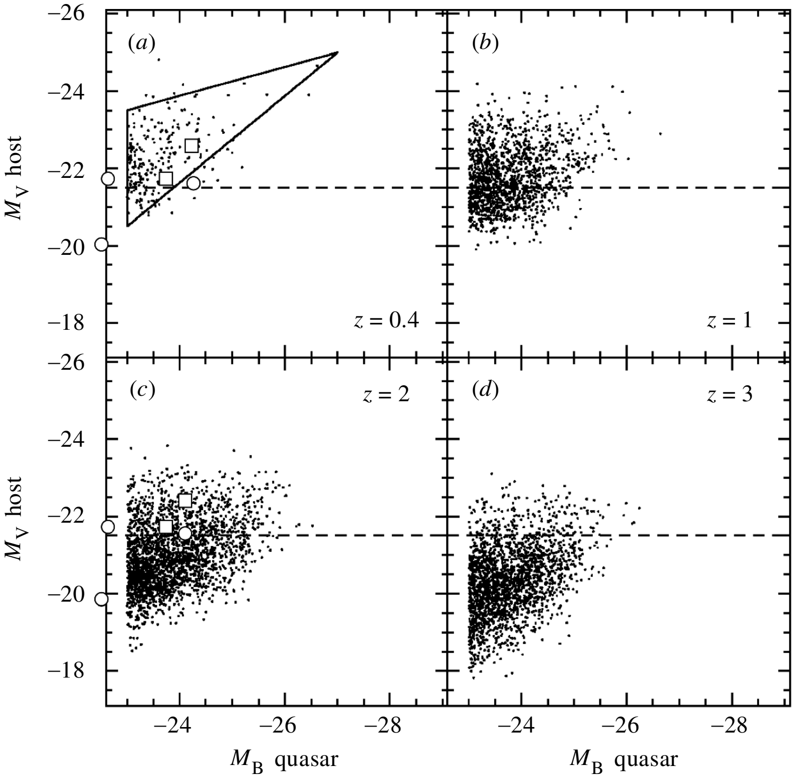

Figure 4. The measured properties of the five radio-quiet $z \sim 2$ quasars and hosts in the Ridgway *et al*. (1999) sample (empty symbols) overplotted on the theoretical predictions from Kauffmann & Haehnelt (1999, their figure 12). The data have been plotted at both $z = 2$ ($c$) for comparison with the models (dots) and at $z = 0.4$ ($a$) to compare with observations of low-$z$ hosts (indicated by the triangular region) (see Ridgway *et al*. (1999) for details). Rix *et al*. (1999) found similar results for more luminous $z \sim 2$ radio-quiet quasars.

(2) As such, they are much fainter than radio galaxies at the same redshift (typically by *ca.* 2 mag).

(3) These host galaxies are, if anything, *less* luminous than the hosts of similarly powerful low-$z$ radio-quiet quasars. Since the luminosity-weighted mean age of the stellar population in the high-$z$ hosts is almost certainly younger than that of the low-$z$ hosts, the difference in stellar *mass* will be even more pronounced.

(4) The rest-frame visual luminosities and sizes of the radio-quiet quasar hosts are roughly similar to those of the LBGs. Thus, the Lyman-break population *might* represent the parent population of typical radio-quiet quasars. Our cycle 8 HST observing programme will determine whether this similarity extends into the rest-frame UV.

The potential implications of these results are quite tantalizing. First, they imply that the well-studied cosmic evolution of the hosts of the very-radio-loud AGN population is evidently *not* representative of the much-more-numerous radio-quiet population. Second, if we make the simplifying assumptions that the ratio of $L_{\rm quasar}/M_{\rm SMBH}$

is roughly independent of redshift and that $M_{\mathrm{SMBH}} \propto M_{\mathrm{sph},z=0}$, then it follows that super-massive black holes form well before their host galaxies are fully assembled. This agrees qualitatively with the idea of the hierarchical assembly of massive galaxies at late epochs. Indeed, as already pointed out by Rix *et al*. (1999) and Ridgway *et al*. (1999), the observations (figure 4) agree rather well with the recent theoretical predictions of Kauffmann & Haehnelt (1999).

## 6. Summary

If the reader takes away only four ideas from my contribution, I hope that they are the following.

(1) Starburst galaxies are good analogues (in fact, the only plausible local analogues) to the known population of star-forming galaxies at high redshift.

(2) Integrated over cosmic time, supernova-driven galactic winds (‘superwinds’) play an essential role in the evolution of galaxies and the IGM.

(3) Circum-nuclear starbursts are an energetically significant component of the Seyfert phenomenon.

(4) The evolution of the population of the host galaxies of radio-quiet quasars is significantly different from that of powerful radio galaxies, and is at least qualitatively consistent with the standard picture of the hierarchical assembly of massive galaxies at relatively late times.

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