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Ultraluminous starbursts from supermassive black hole-induced outflows

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ABSTRACT

I argue that there are two modes of global star formation. Discs and smaller spheroids form stars relatively inefficiently as a consequence of supernova-triggered negative feedback via a sequence of ministarbursts (S mode), whereas massive spheroids formed rapidly with high efficiency via the impact of active galactic nucleus (AGN) jet-triggered positive feedback (J mode) that generates and enhances ultraluminous starbursts. Supermassive black hole growth by accretion is favoured in the gas-rich protospheroid environment as mergers build up the mass of the host galaxy and provide a centrally concentrated gas supply. Quasi-spherical outflows arise and provide the source of porosity as the energetic jets from the accreting central supermassive black hole (SMBH) are isotropised by the inhomogeneous interstellar medium in the protospheroid core. Super-Eddington outflows occur and help to generate both the SMBH at high redshift and the strong positive feedback on protospheroid star formation that occurs as dense interstellar clouds are overpressured and collapse. SMBH form before the bulk of spheroid stars, and the correlation between spheroid velocity dispersion and supermassive black hole mass arises as AGN-triggered outflows limit the gas reservoir for spheroid star formation. The super-Eddington phase plausibly triggers a top-heavy initial mass function (IMF) in the region of influence of the SMBH. The Compton-cooled Eddington-limited outflow phase results in a spheroid core whose phase space density scales as the inverse $5/2$ power of the core mass, and whose mass scales as the $2/3$ power of SMBH mass. This latter scaling suggests that SMBH growth (and hence spheroid formation) is antihierarchical.

Key words: stars: formation: general – galaxies: star formation – cosmology: black holes.

1 INTRODUCTION

It has long been argued on the basis of galaxy colours that star formation is bimodal. Discs are blue and have extended star formation over a Hubble time. Ellipticals, S0s and bulges are red, and are required to have formed in a burst of star formation that lasted $\sim 10^8$ yr. Very different star formation efficiencies are inferrred, and this requirement has motivated the idea that there might be two distinct star formation modes, one possibly associated with a top-heavy initial mass function (IMF) (e.g. Larson 1986; Sandage 1986).

In fact, the situation is not completely bimodal. Modelling of spectral-energy distributions requires the star formation rate in discs, conveniently parametrized by $b = \mathrm{SFR}/\langle \mathrm{SFR}\rangle$, to vary from ~ 0.1 in early-type discs to ~ 10 in late-type discs. Moreover, the past history of star formation in the solar neighbourhood is not monotonic, showing signs of minibursts of star formation (Rocha-Pinto et al. 2000). Also, many nearby early-type galaxies, ellipticals and S0s, show traces of ongoing or recent star formation when observed in the far-ultraviolet. The rates are low, and consistent with a very low efficiency, $b = 0.01$–0.001. In contrast, high-redshift observations of ultraluminous infrared galaxies (ULIRGs) at $z \sim 6$, where the high star formation rate is indicative of elliptical formation, require an extremely high efficiency of star formation.

Clearly, the concept of two modes of global star formation is likely to be an oversimplification of the physical situation. However, for any specified gas initial supply, it is clear that star formation is intrinsically inefficient in discs and relatively efficient when ellipticals formed. The inefficiency of star formation in cold, gas-rich discs is reasonably well understood as a consequence of disc gravitational instability and supernova-driven feedback (Silk 1997, 2003; Efstathiou 2000).

Another requirement is outflow. Galactic winds are required in order to account for the enrichment of the warm intergalactic medium and intracluster gas. Winds are both predicted and observed in dwarfs, but are more problematic for massive galaxies, at least in so far as the theory is concerned. Some evidence for substantial outflows from massive galaxies at high redshift is inferred directly for Lyman break galaxies at $z \sim 3$ that display offsets between stellar and (blueshifted) interstellar spectral lines as well as possible Mpc-scale cavities in the surrounding intergalactic medium (IGM; Adelberger et al. 2003; Shapley et al. 2003), and for ULIRGs where high velocity cold outflows are observed. That the Lyman break galaxies are indeed massive systems has recently been verified (Adelberger

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et al. 2005) by their clustering properties at $z \sim 2$. In the case of our own galaxy, approximately half of the baryons initially present most likely were ejected (Silk 2003). This presumably ends up in the IGM (both photoionized Lyman alpha forest and collisionally ionized warm–hot intergalactic medium, hereafter WHIM), which together contain about half of the baryons in the universe, enriched to approximately 10 per cent of the solar metallicity at the present epoch. In summary, a plausible case can be made that a mass in baryons of order that in stars must have been ejected in the early stages of galaxy formation.

In this note, I develop a complementary theory of efficient star formation in protospheroids that is appropriate to ultraluminous starbursts and massive spheroid formation. The initial phase of black hole growth is associated with super-Eddington accretion: this both allows rapid supermassive black hole (SMBH) growth at high redshift and efficient star formation feedback induced by super-Eddington outflows. Other outcomes include the predictions of momentum-driven winds from ULIRGS with $v_{\rm w} \overset{\propto}{\sim} \dot{M}_*^{1/2}$, a spheroid core phase space density that scales with core mass $M_{\rm c}$ as $\rho_{\rm c}/\sigma_{\rm g}^3 \propto M_{\rm c}^{-5/2}$ and a supermassive black hole mass that scales as $M_{\rm BH} = f_{\rm g}(\sigma_{\rm T}/G^2 m_{\rm p})\sigma_{\rm g}^4$ and $\propto M_{\rm c}^{2/3}$.

Some of these ideas are not new. The notion that outflow from a quasar phase quenches both black hole growth and star formation in such a way as to account for the observed correlation between mass of the SMBH and spheroid velocity dispersion was pioneered by Silk & Rees (1998) and implemented in recent simulations of galaxy formation (Romano et al. 2002; Granato et al. 2004; Di Matteo, Springel & Hernquist 2005). The case for a super-Eddington SMBH growth phase was made by Haiman (2004). Triggering of star formation in radio lobes has been proposed to explain the alignments of optical continuum and emission along the radio axis (De Young 1989; Rees 1989). Extensive star formation as well as generation of intergalactic magnetic fields and metal enrichment has been argued to occur during the peak of quasar activity ($1.5 \lesssim z \lesssim 3$) (Gopal-Krishna & Wiita 2003; Gopal-Krishna, Wiita & Barai 2004). The general connection between active galactic nuclei (AGNs) and spheroid formation was proposed and developed by Chokshi (1997). The novel idea put forward here is to incorporate many of these ideas into the modern view of hierarchical galaxy formation. Star formation time-scales are the key to understanding how discs and spheroids are formed. Supernova-induced feedback controls disc and dwarf galaxy formation by rendering star formation relatively slow and inefficient. Active galactic nucleus (AGN) outflows trigger star formation on a short time-scale by overpressuring protogalactic clouds. Hence they provide an efficient star formation mode before the combined momentum input from both the outflows and supernovae (SNe) eventually drives out the residual gas, suppresses SMBH growth by accretion, and terminates the starburst.

2 DISC MODE

I summarize here the key elements of a simple model for global star formation in discs (Silk 2003). A key parameter in the model is the filling factor $f_{\rm h}$ of hot gas which can be expressed in terms of the porosity Q by $1 - e^{-Q}$. The star formation rate in a disc containing $M_{\rm gas}$ in cold gas and with gas fraction $f_{\rm g}$ is $\dot{M}_* = Q\epsilon M_{\rm gas}\Omega = \alpha_{\rm S} f_{\rm g} v_{\rm circ}/G$, where Q is the porosity, $\epsilon = (\sigma_{\rm g}/\sigma_{\rm f})^{2.7}$, and $\alpha_{\rm S} = Q\epsilon = \sigma_{\rm g} v_{\rm cool} m_{\rm SN}/E_{\rm SN}$. Here Ω is the disc-rotation rate, $v_{\rm circ}$ is the maximum rotation velocity, $\sigma_{\rm g}$ is the gas velocity dispersion, $E_{\rm SN}$ is the kinetic energy of a supernova, $m_{\rm SN}$ is the mass in forming stars required to produce a Type II supernova (approximately 200 $\mathrm{M}_\odot$ for a Kroupa IMF). Also $v_{\rm cool} \approx 400\,\mathrm{km\,s^{-1}}$ is the shell velocity at which strong radiative energy losses set in and $\sigma_{\rm f} \approx 20\,\mathrm{km\,s^{-1}}(E_{\rm SN}/10^{51}\,\mathrm{erg})^{0.6}(200\,\mathrm{M}_\odot/m_{\rm SN})^{0.4}$ is a fiducial velocity. The latter is likely to be a lower bound due to allowance for more realistic physics such as enhancements of porosity due, e.g., to Rayleigh–Taylor instabilities and deviations from spherical symmetry.

The basic idea is that supernovae explosively blow hot bubbles into the protogalactic interstellar medium. The bubbles decelerate by sweeping up shells of cold gas and eventually break up when the expansion is halted by the ambient pressure. If the rate of bubble formation is sufficiently high, the bubbles overlap and a multiphase medium develops of hot shell-shocked gas in which dense cold-shell fragments are embedded. If the hot gas permeates through the cold-gas scaleheight, galactic fountains, chimneys and outflows will result. These phenomena, in what I refer to as the S mode of star formation, result in negative feedback as a consequence of the supernova input. It is for this reason that the gas supply for star formation is limited but long-lived.

This simple analytic model appears to incorporate at least some of the crucial physics and has successfully been tested against simulations of a kiloparsec cube of the interstellar medium (Slyz et al. 2005). One can reproduce the extreme star formation rate in a starburst as well as the more quiescent low efficiency star formation that persists for up to a Hubble time. For a typical gas turbulent velocity (the relative motions of cold clouds), the star formation efficiency $\alpha_{\rm S} = Q\epsilon$ is

$$\approx 0.02\left(\frac{\sigma_{\rm gas}}{10\,\mathrm{km\,s^{-1}}}\right)\left(\frac{v_{\rm c}}{400\,\mathrm{km\,s^{-1}}}\right)\left(\frac{m_{\rm SN}}{200\,\mathrm{M}_\odot}\right)\left(\frac{10^{51}\,\mathrm{ergs}}{E_{\rm SN}}\right).$$

The observed mean value is 0.017 (Kennicutt 1998).

Self-regulation enters in the following way. In discs, the feedback is initially positive but becomes negative once gas can vent out in fountains. Negative feedback and low efficiency is essential for understanding gas-rich disc longevity. Q is expected to be of order unity, as indeed self-regulation plausibly requires. In starbursts, star formation is concentrated and more efficient. The turbulent momentum driving is larger ($\alpha_{\rm S} \propto \sigma_{\rm g}$) whereas the porosity is low, because the increase in the porosity efficiency parameter ($\epsilon \propto \sigma_{\rm g}^{2.7}$) overwhelms the increase in $\alpha_{\rm S}$. At low porosity, the initial feedback is positive.

Local starbursts can be modelled in detail. Incorporation of a Schmidt–Kennicutt star formation law relating the star formation rate to local cold-gas density fails to explain the extended nature of the star formation observed in merging galaxies (Schweizer 2004). Incorporation of turbulence into the expression for star formation provides a greatly improved model for star formation in the Mice, a nearby pair of merging galaxies (Barnes 2004).

One immediate success of such a turbulent star formation model is a refined fit to modelling star formation in merging galaxies. Star formation globally is interpreted as a series of ministarbursts. The gas supply is regulated by infall of small gas-rich satellites. The Milky Way is an interesting case study. The high-velocity clouds may be manifestations of such objects. There is increasing evidence for past minor mergers, a form of gas accretion, from combining chemical and dynamical tracers of high-velocity stars. Chemical signatures associated with the disruption of the Arcturus stream and with ω Cen, and kinematical modelling of the Sagittarius dwarf tidal stream, all point towards a merging history which leaves behind relic stellar tracers (Helmi 2004; Navarro, Helmi & Freeman 2004). Such merging events would have injected a sporadic supply of gas that temporarily reinvigorated star formation. Evidence for such 'ministarbursts' is seen in the local history of star formation as traced by chromospheric dating of nearby stars (Rocha-Pinto et al. 2000). Even on the scale of individual star-forming clouds and young stellar associations, there is empirical evidence that star formation is accelerating (Palla & Stahler 2000), and this has been interpreted as evidence for ministarbursts (Silk 2004).

Perhaps one of the strongest arguments for a ministarburst history in galaxies of stellar mass up to $\sim 10^{10}\,\mathrm{M}_\odot$ comes from recent studies of luminous infrared galaxies at $z > 0.4$ (Hammer et al. 2004) and of the mass–metallicity relation in the local universe (Tremonti et al. 2004). The high frequency of so-called Luminous Infrared Galaxies (LIRGs) argues for an episodic or bursty star formation history in intermediate mass galaxies. Moreover, evidence for metal loss via winds is inferred not just for dwarfs but for moderately massive galaxies. Quiescent disc star formation cannot drive outflows from such galaxies. A series of blow-out events associated with ministarbursts may suffice. Accumulating evidence from studies of the local universe suggests that nearby starbursts typically occur in sub-L_* galaxies and have outflows of order the star formation rate, at least for the handful of well-studied examples, e.g., Martin (2002).

The outflow rate can be estimated to be the product of the supernova rate, the hot-gas filling factor, and the mass loading factor (Silk 2003). The latter depends on such effects as Kelvin–Helmholtz instabilities that entrain cold gas into the hot phase.

In a starburst, one can now express the rate of gas outflow as $\dot{M}_{\mathrm{outflow}} = (1 - e^{-Q})\dot{M}_* f_{\mathrm{L}} \sim Q^2 \epsilon \dot{M}_*$. Rewriting this in terms of the gas mass, $\dot{M}_{\mathrm{outflow}} \approx f_{\mathrm{L}} \alpha_{\mathrm{S}}^2 \epsilon^{-1} M_{\mathrm{gas}} \Omega$. Here f_{L} is the mass-loading factor associated with entrainment of cold gas and depends on the detailed structure of the interface between hot- and cold-gas phases. Kelvin–Helmholtz instabilities will enhance mass loading. Observationally, we know that for at least one nearby starburst, $f_{\mathrm{L}} \sim 10$ (Martin 2002). One can attain $\dot{M}_{\mathrm{outflow}} \sim \dot{M}_* \sim 0.1 M_{\mathrm{gas}} \Omega$ in dwarf starbursts, where the preceding estimates yield $\alpha_{\mathrm{S}} \sim 0.1$, $Q \sim 0.1$, and $\epsilon \sim 1$. However, for starbursts in deep potential wells, so that $\sigma_{\mathrm{g}} \gg 30\,\mathrm{km\,s}^{-1}$, one has $\epsilon \gg 1$, and outflows induced by supernovae are suppressed.

Even inclusion of such effects as cloud disruption as well as more realistic geometries and porosity boosting via inclusion of Kelvin–Helmholtz and Rayleigh–Taylor instabilities are unlikely to raise σ_{f} by more than a factor of 2. One can gain perhaps another factor of 2–3 by allowance for hypernovae and especially by inclusion of a top-heavy IMF. Galactic outflows cannot escape from potentials where the escape velocity exceeds $\sim 100\,\mathrm{km\,s}^{-1}$, if supernova-driven. Nor is there any effective supernova-driven feedback unless $\sigma_{\mathrm{f}} \propto E_{\mathrm{SN}}^{0.6} m_{\mathrm{SN}}^{-0.4}$ is significantly boosted over the value expected for a standard IMF and supernova energy. The porosity is simply too low.

3 SPHEROID MODE

It has long been conjectured that mergers of gas-rich galaxies trigger violent star formation associated with spheroid formation. However, there is no detailed modelling of the conversion of gas into stars and hence of the star formation efficiency. The Schmidt–Kennicutt star formation law, in which star formation rate per unit area is proportional to the product of gas-surface density and disc-rotation rate, fits nearby discs and starbursts. Nevertheless, this approach must be inadequate in the more extreme situations associated with spheroid formation, and even, for example, with ULIRGs, where extremely high star formation efficiencies are inferred.

Specifically, adoption of a universal star formation efficiency results in challenges to the comparison of semi-analytical galaxy formation models with the observational data. The predicted colour and age distributions, alpha element-to-iron abundance ($[\alpha/\mathrm{Fe}]$) ratios relative to solar, and infrared/submillimeter galaxy counts are all in conflict with results from recent surveys (e.g., Thomas et al. 2005).

It seems unlikely that supernovae can account for the high star formation efficiency inferred in the early universe, associated with spheroid formation. Supernova-driven gas flows cannot fill massive galaxy potential wells, and cannot cope with the overcooling problem common to simulations, whereby an excess of massive galaxies is formed. In more extreme situations, supernovae cannot drive the massive galactic outflows that are observed especially at high redshift. Here, one can also cite the enrichment of the IGM, and more directly, the strong radio sources that are centrally dominant cluster galaxies with extended Lyman alpha emission (Reuland et al. 2003), Lyman break galaxies and ULIRGs. Clearly, one needs an additional energy source.

A resolution to both the star formation efficiency and wind dilemmas most likely comes from allowance for SMBH-induced outflows. Suppose that SMBH outflows provide an explanation for the correlation between black hole mass and spheroid velocity dispersion via their effect on gas retention and possibly also on star formation in the protogalaxy. The correlation between central black hole mass and spheroid velocity dispersion suggests that the black hole forms contemporaneously with (Dietrich & Hamann 2004) or even before the stellar spheroid (Walter et al. 2004).

There is indeed a natural coupling, since the SMBH undergoes most of its growth in the gas-rich phase and the SMBH outflow pressurises the gas. Once the stars have formed, the outflow is irrelevant.

We also know from the observed local space density of SMBH and the quasar luminosity function that, if quasars radiate near the Eddington limit, radiatively inefficient accretion is largely responsible for black hole growth (Soltan 1982; Yu & Tremaine 2002). One infers that black hole mergers play a subdominant role in growing SMBH, unless the radiative efficiency is implausibly high and the amount of accretion inferred is thereby reduced. However, to account for the highest redshift, ultraluminous quasars, formation of SMBH at $z \gtrsim 6$–7 in the time available requires super-Eddington accretion rates (cf. Haiman 2004) as well as seed black holes of at least $\sim 1000\,\mathrm{M}_\odot$ (Islam, Taylor & Silk 2004).

A bipolar gas outflow is likely to be an inevitable consequence of SMBH formation via disc accretion. The gas-rich protogalaxy provides the ideal accretion environment for forming the SMBH. Overpressured cocoons, as inferred for high redshift radio galaxies, engulf and overpressure interstellar clouds (Begelman & Cioffi 1989). A broad jet that propagates through an inhomogeneous interstellar medium with a low dense cloud filling factor is disrupted and isotropises (Saxton et al. 2005) to form an expanding cocoon. The hot-plasma cocoon overpressures cold clouds and induces collapse within the central core of the forming galaxy. Star formation is triggered coherently and rapidly in what I refer to as the J mode. The feedback is positive, as there is insufficient time for the supernova-driven negative feedback to develop. The interaction of the outflow with the surrounding protogalactic gas at first stimulates star formation on a short time-scale, 10^7 yr or less, but will eventually expel much of the gas in a wind. Evidence has been found for jet-stimulated star formation up to $z \sim 5$ (Venemans et al. 2004, 2005), followed in at least one case by a starburst-driven superwind (Zirm et al. 2005).

One may crudely describe this situation by modelling the late-time cocoon-driven outflow as quasi-spherical, and use a spherical shell approximation to describe the swept-up protogalactic gas. Initially, following Begelman & Cioffi (1989), the interaction of the pair of jets may be modelled by introducing an overpressured and much larger cocoon, the ends of which advance into the protogalactic gas at a speed v_J determined by the jet thrust independently of the ambient pressure, and which expands laterally at a speed determined eventually by pressure balance with the ambient gas. I first express the jet luminosity L_J in terms of the critical luminosity needed to expel all of the protogalactic gas.

If outflow limits the spheroid star formation by depleting the gas supply (Silk & Rees 1998; King 2003), one has a critical luminosity $L_{cr}/v_J = GMM_g/r^2 = f_g\sigma_g^4/G$, where f_g is the initial gas fraction. If $L_{cr}/v_J = L_{Edd}/c = 4\pi G\kappa^{-1}M_{BH}$, where κ is the electron-scattering opacity, it follows that $M_{BH} = f_g\sigma_g^4\kappa/4\pi G^2$. This is the observed correlation, in slope and normalization (Ferrarese & Merritt 2000; Gebhardt et al. 2000; Onken et al. 2004). The earlier short-lived phase of efficient star formation is induced by outflow luminosities that are super-Eddington. To estimate this effect, first consider the jet/cocoon-protogalactic gas interaction.

In the initial outflow phase, radial momentum flux balance sets L_J/v_J equal to $\rho_a\, R_h^2\, v_h^2$, where R_h is the hot-spot radius. Transverse momentum flux balance controls the lateral expansion of the cocoon, which is wider than the hot spot because of jet precession, and sets L_J/v_h equal to $\rho_a R_c^2 v_c^2$, where R_c is the cocoon width, v_c is the cocoon expansion velocity, ρ_a is the ambient gas density, and $v_h > v_c$ is the hot-spot velocity. I identify v_h with the wind velocity v_w and infer that

$$\frac{L_J}{L_{cr}} = \frac{f_c}{f_g}\left(\frac{v_c}{\sigma_g}\right)^2\left(\frac{v_w}{v_J}\right)^2 = \frac{f_c}{f_g}\left(\frac{v_w}{\sigma_g}\right)^2\left(\frac{R_h}{R_c}\right)^2,$$

where f_c is the baryon compression factor in the core, enhanced due to mergers. One expects in order of magnitude that $(f_c/f_g)(R_h/R_c)^2 \sim 1$. Hence the early outflow is plausibly super-Eddington by a factor of order $(v_w/v_c)^2$ until the cocoon becomes quasi-spherical when its static pressure exceeds the time-averaged jet ram pressure. Expansion continues until the cocoon ceases to be overpressured once $v_c \sim \sigma_g$.

Only a small fraction of the protogalactic gas reservoir is implicated in AGN feeding, even if this occurs at the maximum (Bondi) accretion rate. Super-Eddington outflow of course requires super-Eddington accretion which is plausibly associated with an Eddington luminosity-limited luminous phase implicated in the need to generate massive SMBH by $z \sim 6$ (cf. Volonteri & Rees 2005). As the hierarchy develops, gas-rich mergers replenish the gas supply. A time-scale of 10^6–10^7 yr for the super-Eddington phase would more than suffice to provide the accelerated triggering of star formation associated with the J mode.

Once the jet is quenched, the super-Eddington phase is followed by a longer duration period of Eddington-limited accretion which lasts as long as the fuel supply is available and eventually tapers off into periods of sub-Eddington accretion. The duty cycle of the radio jet phase, associated with the sub-Eddington accretion phase, is correspondingly small.

The SMBH grows mostly in the super-Eddington phase while most of the spheroid stars grow during the Eddington phase. The latter phase ends by quenching the feeding source, when the outflow clears out the remaining gas. Only then is spheroid star formation terminated. Hence the SMBH forms before of order half of the spheroid stars.

To clarify the connection between the AGN outflow luminosity and star formation rate, I write the critical condition for gas outflow when the injected momentum flux, including both sources, can no longer be contained by self-gravity. One has

$$M_g\dot{v} = L_{Edd}/c + \dot{M}_{outflow}v_\infty - GMM_g/r^2,$$

where I have included the momentum input both from the Eddington-luminosity-limited accreting and radiating SMBH and the supernova-driven outflows associated with protogalactic star formation, and v_∞ is the asymptotic wind-flow velocity. Disruption occurs if $L_{Edd}/c + \dot{M}_{outflow}v_\infty$ exceeds $(M_g/M)\sigma_g^4/G$. As before, the outflow rate is related to the spheroid velocity dispersion via the star formation rate, $\dot{M}_{outflow} = Qf_L\dot{M}_*$.

It follows that

$$M_{BH} = \frac{\kappa}{4\pi G^2}\sigma^4\left(\frac{M_g}{M}\right)\left(1 - f_L\alpha_S\left(\frac{\sigma_f}{\sigma_g}\right)^{2.7}(v_w/\sigma_g)\right).$$

I infer that supernova-driven galactic outflows dominate until $\sigma_g \approx (f_L\alpha_S v_w)^{0.3}\sigma_f^{0.7}$, which can be as large as $\sim$100 km s^{-1}. At larger gas turbulence velocities, black hole-driven outflows dominate. This provides a possible demarcation in star formation efficiency at around $M_* \sim 3 \times 10^{10}\,M_\odot$, resembling a trend seen in the SDSS data (Kauffmann et al. 2003). if BH outflow domination is associated with higher efficiency.

The main outcome is the observed relation between black hole mass and spheroid velocity dispersion. Moreover, the variance in the predicted correlation between black hole mass and spheroid velocity dispersion is likely to be controlled and kept small by the self-regulation between supernova-stimulated and Eddington wind-triggered star formation. If some outflows are sub-Eddington, as seems likely over long times, an asymmetric variance results in the relation between black hole mass and spheroid velocity dispersion.

I now compare the two modes of star formation, writing $\dot{M}_* = \alpha_{S,J} f_g\sigma_g^3/G$, where $\alpha_S = \sigma_g v_c/E_{SN}m_{SN}$ and α_J is set by the super-Eddington outflow, $L_J \sim f_c v_h v_c^2\sigma_g^2/G$. The super-Eddington phase is plausibly associated with the quasar phenomenon, the black hole outflow being aided and abetted by triggered massive star formation.

The outflow is super-Eddington until the cocoon is limited by ambient pressure and becomes quasi-spherical. As the massive star formation/death rate slows, the AGN feeding augments and the outflow stimulates more star formation. The star formation has negative feedback on AGN feeding, the AGN feeding has positive feedback on star formation. If this conjecture is correct, then $\dot{M}_*^E \sim L_J/cv_\infty \sim f_c\sigma_g v_w v_c^2/v_J G$, so that $\alpha_J \sim (f_c/f_g)(v_w/v_J)(v_c/\sigma_g)^2 \sim 1$.

One could speculate that the super-Eddington phase is biased towards forming primarily massive stars. Such a top-heavy IMF is actually inferred in the Arches cluster (Stolte et al. 2002), the most massive young galactic star cluster and within 30 pc of the central supermassive black hole. One could even speculate that the massive OB stars found within a parsec of SgrA* could have been formed by a brief phase of SMBH outflow a million or so years ago. A top-heavy IMF would also help explain the enrichment and abundance ratios in intracluster gas (Nagashima et al. 2005) and in quasar emission line regions (Dietrich et al. 2003), the very high luminosities inferred in some ULIRGs relative to the available gas supply, and the Submillimeter Common-User Bolometer Array (SCUBA) counts of submillimetre galaxies (Baugh et al. 2005). A top-heavy IMF would also provide an attractive source of black hole seeds for SMBH growth. The high [α/Fe] ratios observed systematically in massive spheroidal galaxies can be qualitatively understood since both α_S and α_J are proportional to σ_g. Hence in lower-mass spheroids the low-mass stars form relatively less efficiently and hence more slowly, thereby diluting the enhanced [α/Fe], associated with massive star SNII yields, with the iron from low-mass star SNIa yields.

There are other consequences of this model. The cocoon expansion velocity satisfies $v_c = (v_h v_J)^{1/2}(R_h/R_c)$, so that in the super-Eddington phase $\dot{M}_* \propto v_c^2 v_w \sigma_g / v_J \overset{\propto}{\sim} v_w^2$, since $v_h \approx v_c$. Hence the naive prediction of the model is that for ULIRGs, one should find flows with $v_w \overset{\propto}{\sim} \dot{M}_*^{1/2}$. Moreover, these, in contrast to supernova-driven flows which are driven by bubble energy of the hot phase, are momentum-driven by the Compton-cooled AGN wind. Neutral flows are expected, and the trend seen in NaI absorption for ULIRG cold outflows is consistent with this model prediction (Martin 2005).

The Eddington phase coupling of wind and induced starburst-driven outflows suggest that one will generally have $\dot{M}_* = \alpha_S \sigma_g^3/G \propto \sigma_g^4$, yielding an accounting for the Faber–Jackson relation with approximately the correct normalization (cf. Murray, Quataert & Thompson 2005).

Finally, I turn to core scalings. Begelman & Nath (2005) argue that feedback energy is regulated by the momentum deposition on the accreting gas in the region where the outflow from the black hole first undergoes strong cooling. The accretion is Eddington limited and this yields the correlation between core-velocity dispersion and black hole mass. The model presented here similarly has momentum coupling and so not surprisingly yields a similar scaling. The final stellar core size is expected to be of order the Bondi radius, within which black hole gravity dominates over that of the spheroid. However, the detailed core properties, and in particular the core scale, must also depend on the extent of the region where the momentum is effectively injected into the accretion flow. The following simple model illustrates the impact of feedback both on black hole growth and on the core scale.

The onset of Compton cooling determines the end of the energy-conserving phase of the jet and the onset of the momentum driving that generates the cocoon and the surrounding dense shell. I argue that this sets the core scale, which coincidentally can be shown to be of order the Bondi radius. The AGN relativistic jet-induced plasma outflow undergoes Compton cooling at a radius determined by setting the flow time equal to the Compton cooling time-scale. This yields $R_c = M_{BH}(m_p/m_e)^2(G v_w/c^3)$, where $v_w \gtrsim 0.1c$. Comparing R_c to the zone of influence of the SMBH, the Bondi radius, $R_B = G M_{BH} \sigma_g^{-2}$, one finds that $R_c = R_B(\sigma_g/c)^2(m_p/m_e)^2(v_w/c) \sim R_B$.

Now R_B is a plausible scale for the cores of spheroids, as supermassive black holes, and in particular decays of massive binary black holes (Lauer et al. 2005), are conjectured to have played a role in determining the core cuspiness or lack thereof by dynamical interactions with the spheroid stars. One can now demonstrate that the core mass is $G^{-2}\beta\sigma_g^6$, where $\beta = f_g(\sigma_T/m_p)(m_p/m_e)^2(v_w/c^3) \approx 10^{-16} f_g(v_w/c)\,\mathrm{s^2\,g^{-1}}$. This leads to two predictions.

The core phase space density (assuming the cooled gas forms the core stars) is

$$\frac{\rho_c}{{\sigma_g}^3} = \beta^{1/2} f_g^{-1} M_c^{-5/2} \propto M_c^{-5/2}.$$

This is close to the observed core scaling of core phase space density with mass (Carlberg 1986; Faber et al. 1997).

Also the ratio of SMBH to core mass is $M_{BH}/M_c = \sigma_g^{-2}(m_e/m_p)^2(c^3/v_w) \propto M_c^{-1/3}$. This means that there is a greater reservoir of cooled gas for the more massive black holes. Hence formation of massive SMBH should be favoured over those of lower mass. This provides at least a qualitative antihierarchical explanation of the observed AGN X-ray luminosity function dependence on redshift (Hasinger, Miyaji & Schmidt 2005). At the same time, the coupling of SMBH outflow to spheroid star formation means that spheroid formation is equally antihierarchical, with massive spheroids in place before the lower-mass systems.

4 CONCLUSIONS

Disc star formation is envisaged as a series of ministarbursts. In a disc, $\sigma_g \approx 10\ \mathrm{km\,s^{-1}}$, so that $\epsilon \approx 0.05$ for $\sigma_f \approx 30\,\mathrm{km\,s^{-1}}$. The observed efficiency is inferred from $\dot{\Sigma}_* = 0.017\Sigma_{gas}\Omega$, and is globally about 2 per cent. This means that $\alpha_S \approx 0.02$ and $Q \sim 0.5$, as is observed for the Milky Way.

In a starburst, however, the star formation efficiency is necessarily higher because $\epsilon \propto \sigma_{gas}^{2.7}$. The surprising phenomenological result is that starbursts also lie on the same Kennicutt fit, $\dot{\Sigma}_* = Q\epsilon\Sigma_{gas}\Omega$, with $Q\epsilon = 0.017$. However, there are two noteworthy differences with quiescent disc star formation. The porosity is low since ϵ is necessarily large. And the overall efficiency of star formation is necessarily high because of the enhanced stellar scale length associated with turbulence and ultimately responsible for driving the starburst. Indeed, spatially extended star formation is seen in mergers. Self-regulation must account for the apparent conspiracy between Q and ϵ.

Starbursts are ubiquitous at high redshift. In fact, starbursts are limited by the local gas supply. Infalling satellites yield a stochastic gas supply. A simple self-regulation hypothesis yields the star formation rate in a range of physical situations, thereby accounting for the Schmidt–Kennicutt law. One can regard quiescent disc star formation as a series of ministarbursts, which seamlessly progresses into the major starburst regime as the gas-supply rate is enhanced. The fact that the phenomenological star formation law accounts both for quiescent discs and low-mass starbursts can therefore be accommodated.

The difference in star formation characteristics between massive and low-mass discs has received attention in a recent study of edge-on discs (Dalcanton, Yoachim & Bernstein 2004). The case is made that the scaleheight increases sharply (by a factor of about 2) as the rotational velocity drops below $120\ \mathrm{km\,s^{-1}}$, simultaneously with an increase in disc gravitational stability to axisymmetric perturbations. This could be due to an increase in gas turbulence or to a decrease in disc surface density. At a given disc mass, one would expect star formation efficiency to globally decrease with higher turbulence, due to the increased effects of disc venting via chimneys and fountains. This trend may be seen in the edge-on disc sample, although detailed simulations are needed in order to explore the theoretical implications that involve the interaction of disc gravitational instabilities, molecular cloud evolution, disc outflows and star formation. One generally finds that lower-mass discs tend to be gravitationally stable and are not self-regulating. The star formation rate is low presumably because the gas supply provided by gravitational instability is reduced. Indeed, systematically lower star formation efficiency in low rotation, low-mass discs seems to be indicated by the data.

A plausible outcome of a starburst is that the mass in gas ejected is of order the mass in stars formed. For low-mass systems, the outflow should escape in a porosity-driven hot wind. It is less certain as to where the gas is ejected. It might be recycled into the disc via fountains and chimneys.

Massive galaxies require a more efficient driver to generate ultraluminous starbursts and winds. Supernovae do not provide enough momentum input to drive winds from L_* galaxies. For this, recourse must be had to AGN-triggered outflows (Benson et al. 2004) in order to inhibit gas accretion which otherwise results in overproduction of overly luminous galaxies in the local galaxy luminosity function. These have the dual purpose of stimulating protogalactic star formation and ultimately driving a strong galactic wind once the black hole mass saturates at the Magorrian–Gebhardt–Ferrarese correlation. Strong winds lead in turn to saturation of the global star formation rate as well as of the supermassive black hole mass. The starburst luminosity is coupled to the Eddington luminosity, which is self-limiting with regard to the gas supply. The star formation rate and Eddington luminosity are anticorrelated and self-regulated via feedback. The predicted AGN triggering of the extreme starbursts associated with protospheroid formation means that AGN signatures should be subdominant but still present in ultraluminous starbursts.

Black holes are in place before most of the spheroid stars have formed, at least in a massive spheroid, since it is the black hole outflows which provide the positive feedback stimulus for massive spheroid star formation. Observations of the $M_{\rm BH}$, $\sigma_{\rm g}$ correlation in AGN even suggest that SMBH formed before the full spheroid potential was in place at very high redshift (Walter et al. 2004). However, the situation is less clear in the nearby universe: SMBH masses determined by AGN emission line reverberation mapping seem to lie both above (Treu, Malkan & Blandford 2004; Peterson et al. 2005) and below (Grupe & Mathur 2004) the ($M_{\rm BH}$, σ_*) correlation, as do, respectively, spectroscopic determinations for an AGN (Silge et al. 2005) and a nearby SB0 galaxy (Coccato et al. 2005).

The supermassive black hole correlation is a natural outcome of gas accretion, SMBH growth and feedback-triggered star formation in the protospheroid. One should also find examples of low-mass SMBHs without spheroids as the feedback argument must inevitably become 'leaky' at low mass. A brief super-Eddington phase is associated with radio-loud quasars and plausibly with top-heavy star formation, and can help account for rapid SMBH formation at very high redshift. Compton-cooled flows are another consequence of outflow-triggered star formation, in that a dense gas reservoir is provided in the cores for SMBH and spheroid star formation. The inferred scaling laws for core phase space density match the observed trend. Antihierarchical SMBH formation is a natural consequence of massive core formation, and this also means that the stellar cores will follow a similar trend with spheroid mass.

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