UNLEASHING POSITIVE FEEDBACK: LINKING THE RATES OF STAR FORMATION, SUPERMASSIVE BLACK HOLE ACCRETION, AND OUTFLOWS IN DISTANT GALAXIES

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ABSTRACT

Pressure-regulated star formation is a simple variant on the usual supernova-regulated star formation efficiency that controls the global star formation rate as a function of cold gas content in star-forming galaxies, and accounts for the Schmidt–Kennicutt law in both nearby and distant galaxies. Inclusion of active galactic nucleus (AGN) induced pressure, by jets and/or winds that flow back onto a gas-rich disk, can lead, under some circumstances, to significantly enhanced star formation rates, especially at high redshift and most likely followed by the more widely accepted phase of star formation quenching. Simple expressions are derived that relate supermassive black hole growth, star formation, and outflow rates. The ratios of black hole to spheroid mass and of both black hole accretion and outflow rates to star formation rate are predicted as a function of time. I suggest various tests of the AGN-triggered star formation hypothesis.

Key words: galaxies: active – galaxies: evolution – galaxies: star formation – Galaxy: formation

1. INTRODUCTION

One of the great mysteries in galaxy formation is the connection with supermassive black holes (SMBHs) and active galactic nuclei (AGNs). AGN outflows are generally thought to play an important role in quenching star formation, as in Nesvadba et al. (2010) and references therein. An impressive recent example of negative feedback driven by a quasar on galactic scales is given by Maiolino et al. (2012).

In rare, usually nearby, cases, there is evidence for triggering of star formation. How prevalent this might be at early epochs is unknown. AGN luminosities and nuclear star formation rates are correlated (Imanishi et al. 2011). Jet triggering of star formation in nearby galaxies (Croft et al. 2006; Rodríguez Zaurín et al. 2007; Crockett et al. 2012), of distant galaxies (Feain et al. 2007; Elbaz et al. 2009), and even of molecular hydrogen cloud formation at high redshift (Klamer et al. 2004) is observed.

There is a quantitative connection between black hole mass and spheroid velocity dispersion ($M_{\rm BH} \overset{\propto}{\sim} \sigma^{4-5}$) with approximate bulge mass scaling $M_{\rm BH} \approx 10^{-3} M_{\rm spheroid}$ (Graham et al. 2011 and references therein), with deviations at low (Graham 2012) and high masses (McConnell & Ma 2013). There is also a relation between black hole accretion rate and star formation rate ($\dot{M}_{\rm BH} \approx 2.10^{-3} \dot{M}_*$) in AGNs (Silverman et al. 2009; Mullaney et al. 2012). Rapid black hole growth and intense host galaxy star formation are inferred to be coeval at $z \sim 6$ (Wang et al. 2011). AGN-heated molecular disks are responsible for black hole growth and show little evidence for star formation (Sani et al. 2012), which however dominates further out. An interesting example of coexisting black hole growth and star formation is the case of IRAS 20551−4250 (Sani & Nardini 2012), where the AGN-heated molecular disk dominates the emissivity at mid-IR wavelengths on ∼100 pc scales but star formation dominates at near-IR (NIR) and far-IR (FIR) wavelengths on kpc scales.

In this paper, I revisit the theory of AGN-triggered star formation, and develop an analytical formulation intended to complement recent simulations, most notably those of Gaibler et al.

(2012). The theory of AGN-triggered star formation was developed in Silk & Norman (2009). Subsequent applications include one-dimensional (Ishibashi & Fabian 2012), two-dimensional (Liu et al. 2013a), and three-dimensional numerical simulations in homogeneous halos (Zubovas et al. 2013). However, only the three-dimensional studies of propagation of jets (Gaibler et al. 2012; Wagner et al. 2012) and winds (Wagner et al. 2013) in inhomogeneous halos capture the appropriate physics of outflows and induced star formation.

One motivation for introducing AGN outflows (jets or winds) as a star formation trigger is that a timescale naturally arises that is shorter than the gravitational timescale (Silk & Norman 2009). I argue below that a shorter timescale at high redshift is motivated observationally. Another is that radiation-pressure-driven outflows are generically leaky because of Rayleigh–Taylor instabilities and fail to provide the momentum needed via multiple scatterings to account for the $M_{\rm BH}$–σ scaling relation (Silk & Nusser 2010; Krumholz & Thompson 2013).

The theory is intended to provide a second mode of star formation, dominant at high redshift and rare at low redshift, that can account for the observed elevated, and more slowly varying at high redshift, specific star formation rate (SSFR), defined by SSFR $= \dot{M}_*/M_*$ (see Weinmann et al. 2011 for a recent compilation of the data, and Bouwens et al. 2012 and Stark et al. 2013 for updates with revised dust and nebular emission corrections, respectively) in luminous star-forming galaxies. The star formation rate phenomenology is outlined in Section 2, and the mechanism for positive feedback is developed in Section 3, where I account for the interconnection between black hole growth, star formation, and outflow rates. A final section provides a summary and discussion of possible tests of the AGN positive feedback hypothesis.

2. STAR FORMATION RATE

My starting point is the well-tested phenomenological expression for the star formation rate in disk galaxies, motivated by the instability of self-gravitating cold gas-rich disks to non-axisymmetric instabilities that lead to fragmentation and giant

molecular cloud formation, with subsequent star formation modulated by feedback from supernovae. This simple formalism fits star-forming galaxy data on the Kennicutt–Schmidt law, both nearby and at $z \sim 2$ (Kennicutt 1998; Genzel et al. 2010), and even fits data on individual star-forming cloud complexes provided the local free-fall time is used instead of $1/\sqrt{G\rho_d}$ (Krumholz et al. 2012), where ρ_d is the mean disk density. I note in passing that not all authors agree on the role of supernova feedback as the primary culprit that controls the normalization of the Kennicutt–Schmidt relation. However, supernova feedback as an explanation of galactic star formation inefficiency is certainly a majority viewpoint.

One may write the star formation rate per unit area in a galactic disk as

$$\dot{\Sigma}_* = \epsilon_{\rm SN}\Sigma_{\rm gas}/t_{\rm dyn},$$

where $\Sigma_{\rm gas}$ is the gas surface density at a disk scale length R_d and $t_{\rm dyn}$ is a disk dynamical time, taken here to be R_d/σ, with σ taken to be the circular velocity. I define the gas pressure in the disk, appropriate for interstellar clouds of velocity dispersion σ_d, by $p_{d,{\rm gas}} = \rho_{d,{\rm gas}}\sigma_d^2$, where $\rho_{d,{\rm gas}}$ is the gas density in the mid-plane, and the dynamical pressure of the gas, appropriate to a gaseous halo component, by $p_{h,{\rm gas}} = \rho_{h,{\rm gas}}\sigma^2 = \pi G\Sigma_{\rm gas}\Sigma_d$. Also, ρ_d is taken to be the total disk density in the mid-plane. I can rewrite the star formation rate in terms of gas pressure (Silk & Norman 2009) as

$$\dot{\Sigma}_* = \epsilon_{\rm SN}\Sigma_{\rm gas}\frac{\sigma}{R_d} = \Sigma_{\rm gas}\frac{\epsilon_{\rm SN}}{\sigma_d}\sqrt{\frac{\pi G p_{d,{\rm gas}}}{f_g}}\sqrt{\frac{h}{R_d}}, \qquad (1)$$

where f_g is the gas fraction and h is the disk scale height. The efficiency of supernova momentum feedback is

$$\epsilon_{\rm SN} = \sigma_d v_c m_{\rm SN}/E_{\rm SN} = 0.02\sigma_{d,10}v_{c,400}m_{\rm SN,150}E_{51}^{-1}. \qquad (2)$$

Here $\sigma_d = 10\sigma_{d,10}$ km s^{-1} denotes the velocity dispersion of molecular clouds, $v_c = 400v_{c,400}$ km s^{-1} is the velocity at which a supernova-driven shell enters the momentum-conserving phase of the expansion, $m_{\rm SN} = 150m_{\rm SN,150}~M_\odot$ is the mass in stars formed per supernova, and $E_{\rm SN} = 10^{51}E_{51}$ erg is the initial energy of the supernova explosion. Recall that Σ_d is approximately constant for star-forming disks (Freeman's law), as is $\Sigma_{\rm gas}$ for molecular clouds (one of Larson's laws), although, for star-forming galaxies, the global value of $\Sigma_{\rm gas}$ may be higher by orders of magnitude in extreme cases.

The star formation efficiency, namely, the fraction of gas converted into stars per orbital time or $\dot{\Sigma}_* t_{\rm dyn}/\Sigma_{\rm gas}$, is equal to $\epsilon_{\rm SN}$. Since $\epsilon_{\rm SN} \propto \sigma_d$, this relation leads to an enhanced efficiency of star formation in merging galaxies as well as in starburst galaxies where gas turbulence is enhanced. This applies to extreme starbursts (García-Burillo et al. 2012), which most likely have merger or AGN-induced turbulent gas motions.

In what follows, I will explore the implications of Equation (1) for AGN-induced pressure. Since this equation is central to my discussion, I first give a more rigorous derivation, based on the linearized gravitational instability of rotating, external-pressure-confined, vertically stratified polytropic gas disks.

The maximum instability growth rate in such disks is found to be enhanced by the external pressure, in a study of self-gravitating disks that are initially in hydrostatic equilibrium (Kim et al. 2012). The usual derivation of the Schmidt–Kennicutt law is

$$\dot{\Sigma}_* = \epsilon_{\rm SN}\Sigma_{\rm gas}\omega_m,$$

where ω_m is the maximum growth rate for the non-axisymmetric gravitational instabilities that control molecular cloud growth and star formation, as derived (cf. Elmegreen 1997; Silk 1997) and applied (e.g., Kennicutt 1998; Genzel et al. 2010). One can now generalize the growth rate to the case of an externally pressure-confined disk:

$$\omega_{m,p} = t_{\rm dyn}^{-1}\left(1 + \frac{2}{\pi}\frac{p_{\rm ext}}{G\Sigma_0^2}\right)^{1/2} \sim t_{\rm dyn}^{-1}(2p_{\rm ext}/p_d)^{1/2}.$$

The star formation law now reduces to

$$\dot{\Sigma}_* = \epsilon_{\rm SN}\Sigma_{\rm gas}\frac{\sigma}{R_d} = \Sigma_{\rm gas}\frac{\epsilon_{\rm SN}}{\sigma_d}\sqrt{4\pi G p_{\rm ext}}\sqrt{\frac{h}{R_d}}.$$

Note that in the simulations performed to date, the external pressure increase on the gas-rich disk is typically ~ 1000 (Gaibler et al. 2012; Wagner et al. 2012). One might expect the linear theory result to set an upper limit on the results of the simulations, as non-linear effects such as cloud destruction by ablation need to be included in any analytic discussion. In fact, the simulations of triggered star formation (Gaibler et al. 2012) show a factor of 3–4 increase in SFR, but the simulations were stopped when the SFR was still increasing.

Another result from Kim et al. (2012) is that the characteristic wavelength of the instabilities is reduced by a factor $\sim 2p_{\rm ext}(\pi G\Sigma_0^2)^{-1}$, or $\sim 2p_{\rm ext}/p_d$. This effect augments the supply of molecular clouds that participate in star formation.

3. AGN FEEDBACK

Accretion onto the central SMBH results in a powerful wind with a broad opening angle or a narrow jet. The latter, propagating into an inhomogeneous interstellar medium (ISM), rapidly develops into a cocoon or bubble once the bow shock that surrounds and precedes the jet thermalizes with the ambient medium.

Building on the beautiful results from adaptive grid numerical simulations that are capable of resolving the Kelvin–Helmholtz instabilities that control the interaction of the AGN outflows with interstellar clouds, I use jet-driven outflows (Wagner et al. 2012) and jet-triggered star formation (Gaibler et al. 2012) as my canonical case in what follows.

However, the energetics of either type of outflow (jet-driven or wind-driven; for simulations of the latter case, see Wagner et al. 2013), expressed in terms of the AGN luminosity, are inevitably similar, with the jet being accompanied by a powerful bow shock, apart from geometrical inefficiency factors that I ignore here.

If indeed interstellar pressure (rather than gas density) is the controlling factor in star formation rate, then we can infer the role of an AGN in driving star formation in the circumnuclear disk by evaluating the contribution of the AGN outflow to the ISM pressure, as developed in Silk & Norman (2009). The ISM pressure due to AGN outflows is

$$p_{\rm AGN} = f_E\frac{L_E}{4\pi R_d^2 c} = f_E G\frac{M_{\rm BH}\Sigma_d}{M_d\kappa}, \qquad (3)$$

where the Eddington luminosity is

$$L_E = \frac{4\pi GcM_{\rm BH}}{\kappa}, \qquad (4)$$

the Eddington accretion rate (or the black hole growth rate at Eddington luminosity) is

$$\dot{M}_E = \dot{M}_{\mathrm{BH}}/f_E = \frac{L_E}{\eta c^2} = 4\pi \frac{GM_{\mathrm{BH}}}{c\eta\kappa}, \qquad (5)$$

and the wind outflow rate from the AGN disk is (King & Pounds 2003)

$$\dot{M}_w = f_E \frac{L_E}{v_w c}. \qquad (6)$$

Here $f_E = f_x L_{\mathrm{AGN}}/L_E$ and κ is the opacity, quantified below and generally taken to be dominated by electron scattering at small radii (or by dust at large radii) in the subsequent applications. I have introduced an (unknown) AGN efficiency factor f_x that might be less than unity to incorporate AGN-driven shell dissipation. This would affect the scalings derived above. For example, a case can be made for energy-conserving winds (Faucher-Giguère & Quataert 2012).

The AGN pressure introduced here drives a wind, in conjunction with any supernovae resulting from triggered star formation. The radial dependence of the overpressured outflow is described below in what I call the far regime via a solution for the pressure-driven shell or ring. So far as the disk is overpressured, this refers to a continuous input of energy via backflow of the circumdisk gas heated by the frustrated jet or wind. This quasi-uniform turbulent pressure behind the bow shock is clearly seen in the numerical simulations (Gaibler et al. 2012; Wagner et al. 2012, 2013).

3.1. The Near and Far Regimes

Quasar feedback is commonly divided into two modes: the quasar and the radio modes. This is a great simplification of course, but captures the essential physics. The M_{BH}–σ scaling relation, and associated black hole growth, is controlled by the quasar mode. Quenching of star formation by gas ejection from the galaxy potential well is regulated by the radio (essentially radio jet) mode. These modes correspond to near and far regimes, with radio jets, and the associated bow shocks, linking the two. The following discussion of the two modes is meant to be illustrative and plausible but could well be modified if different physical models are adopted, for example, with regard to the gas fraction or the dust content.

3.1.1. The Near Mode

In the near, AGN-dominated, regime, the radiative momentum and any associated wind drive gas away. The gas is ionized and hot, and the dominant opacity is electron scattering. The geometry in the inner region will be that of a hot disk but can be approximated here as quasi-spherical.

I assume that the black hole outflow self-regulates the gas reservoir that feeds the disk. Hence, balancing the AGN momentum L_E/c with the acceleration needed to eject a gas shell $\bar{f}_g GM^2 R^{-2}$, where I denote the galaxy-averaged gas fraction by $\bar{f}_g \approx 0.2$, I obtain the well-known expression (Silk & Rees 1998; Fabian 1999; King 2003; Murray et al. 2005) for the M_{BH}–σ relation:

$$\sigma^4 = 4\pi G^2 M_{\mathrm{BH}}/\kappa \bar{f}_g. \qquad (7)$$

This agrees in normalization and slope with the observed relation, although understanding the dispersion in the relation requires substantially more physics input that has largely been lacking up to now.

The gas ejected from the inner region does not acquire enough momentum to be ejected from the galaxy and would eventually cool and refuel star formation, were it not for the onset of jet-driven feedback. I will use jets as my template in what follows since these have hitherto been explored in most detail with high-resolution simulations, but, as noted previously, winds may be equally effective.

3.1.2. The Far Mode

Consider the jet driving of bubbles. The jet power is approximated by the Eddington ratio $f_E = P_{\mathrm{jet}}/L_E$. The jet expands into an inhomogeneous ISM and drives a bow shock. The ram pressure sweeps up a shell of dense gas, entrains clumps, and ablates cold gas. The expanding bubble surface allows a large ram pressure momentum boost over radiative momentum by a mechanical advantage factor $f_p \sim 10$–300 (Wagner et al. 2012, 2013), with the numerical simulations finding an outflow efficiency

$$\dot{M}_w v_w^2/L_{\mathrm{AGN}} = v_w/c \qquad (8)$$

$$= (0.1\text{–}0.4) P_{\mathrm{jet}}/L_{\mathrm{AGN}}. \qquad (9)$$

The momentum acquired by clouds relative to jet momentum due to ram/thermal pressure is $f_p \approx t_3^{1/2}$, where $t_3 = t/1000$ yr. In this approximately energy-conserving phase, $v_w^2 \propto P_{\mathrm{jet}} t R^{-3}$, and one has $R \propto t^{3/5}$, so that

$$f_p \propto R^{5/6} \propto v_w^{-5/4}. \qquad (10)$$

As v_w falls from its initial value $\sim (0.3\text{–}0.1)c$ to the observed outflow velocities of $\sim 10^3$ km s^{-1}, one infers that indeed $f_p \sim 10$–100.

The fully three-dimensional numerical simulations demonstrate the validity of this simple approximation, and supercede earlier discussions that assume spherical symmetry but still provide some insight. For example, an alternative way of viewing the boost is if energy of the initial relativistic outflow is conserved, with a fraction f_i of the initial wind energy going into shell acceleration, generating bulk motion of the swept-up gas at v_{shell}. In this case, the momentum flux is boosted relative to L_{AGN}/c by a factor $f_i v_w/v_{\mathrm{shell}}$, where we might expect $v_w \sim 0.1c$ and $f_i \sim 0.5$ (Faucher-Giguère & Quataert 2012; Zubovas & King 2012). In fact, the actual physics is likely to be rather more complicated, since the final outflow velocity occurs at the onset of the momentum-conserving phase and is a more complex function of halo mass (Silk & Nusser 2010).

First, I give a back-of-the-envelope estimate for the AGN-induced pressure exerted on clouds in the disk or spheroid, namely,

$$p_{\mathrm{AGN}} = f_p f_E \frac{L_E}{4\pi R^2 c}, \qquad (11)$$

where the mechanical advantage factor f_p includes the effects of wind interactions and f_E is the Eddington ratio L_{AGN}/L_E. In what follows, I write $f_{pE} = f_p f_E$, and for fiducial values, I will define $f_{pE} = 30 f_{pE,30}$.

The wind-driven pressure from the entire galaxy is similar:

$$p_w = \frac{\dot{M}_{\mathrm{wind}} v_w}{4\pi R^2} = f_{pE} \frac{L_E}{4\pi R^2 c}. \qquad (12)$$

Next, I derive the pressure more rigorously. Note first that the relevant pressure is ram pressure. I use the similarity solution

for a wind driven by an active region with uniform energy and mass injection (Chevalier & Clegg 1985). This spherically symmetric solution, appropriate to a gas-rich spheroid, has been generalized to the case of axial symmetry and a wind-driven gas ring (Chevalier 1991), relevant to the case of a gas-rich disk, and the spherical solution has been recently generalized to include the effects of a dark matter halo (Sharma & Nath 2013). However, these complications do not significantly modify the scalings that I use here. The similarity solution for the wind shows a smooth transition from subsonic flow at the center to supersonic flow at large radii. The energy injection is due to the AGN jet/wind and the mass injection from cloud destruction and ablation. Additional energy and mass injection will come from triggered supernovae.

The similarity solution is expressed in terms of dimensionless velocity, density, and pressure variables:

$$u_* = u \frac{\dot{M}^{1/2}}{\dot{E}^{1/2}}, \quad \rho_* = \rho \frac{\dot{E}^{1/2}}{\dot{M}^{3/2}} R^2, \quad p_* = \frac{p}{\dot{M}^{1/2}\dot{E}^{1/2}} R^2.$$

The ram pressure is $p + \rho u^2$ for the spherical outflow or $p + \rho(u^2 + (5/18)v_c^2)$ for the expanding ring, where v_c is the disk circular velocity. The pressure (thermal and ram) as well as the density indeed decrease as r^{-2} outside the active region of radius R: all variables are approximately constant within this region, if the star formation rate is proportional to the swept-up mass. This should be true, as anticipated here, in the event that triggered star-formation-induced supernovae add to the AGN energy injection in driving the wind.

3.2. Opacities

A key question here is what to assume for opacity in the outer region where galaxy-wide outflows are driven. In the absence of significant dust, the electron scattering opacity is $\kappa_{\rm es} = \sigma_T/m_p = 0.38 \, {\rm cm}^2 \, {\rm g}^{-1}$. In fact, while electron scattering opacity is appropriate both in the outer protogalaxy and close to the SMBH, where any dust would be evaporated, the situation is different in the galactic core where the massive black hole forms. There is associated massive star formation, which in most theoretical scenarios is a required precursor to SMBH formation (Volonteri 2012). In such situations, there inevitably is metal and dust production during the assembly phase of the central SMBH. Phenomenology demonstrates that cores of spheroids are metal-rich, usually supersolar, and that quasar broad emission line regions are highly enhanced in heavy elements relative to solar values (Simon & Hamann 2010). The latter paper argues that the lack of correlation of metallicity with host galaxy star formation rate suggests that the enrichment occurred at a prior phase, presumably during the coevolution growth phase of the bulges and that of the SMBH.

I adopt a dust opacity at $T \lesssim 200$ K given by the Rosseland mean opacity that depends only on temperature, scaling approximately as

$$\kappa = \kappa_0 (T/T_0)^\beta, \tag{13}$$

where $\kappa_0 T_0^{-2} = 2.4 \times 10^{-4} \, {\rm cm}^2 \, {\rm g}^{-1} \, {\rm K}^{-2}$, and is valid at $T \lesssim T_0 \equiv 100$ K (Semenov et al. 2003). This is appropriate in the FIR regime, for $h\nu \lesssim kT$. The dust opacity rises steeply with increasing frequency, and a typical dust opacity in the UV is $\sim 100 \, {\rm gm} \, {\rm cm}^{-2}$.

In the vicinity of the AGN, the dust grains are heated beyond their sublimation temperature. The dust sublimation radius for the most refractory grains, pure graphite cores with

a sublimation temperature $T_{\rm sub}$ of 1800 K, is (Kishimoto et al. 2012)

$$R_{\rm sub} = 0.5 \left(\frac{L_{\rm bol}}{10^{46} \, {\rm erg} \, {\rm s}^{-1}} \right)^{1/2} \left(\frac{1800 \, {\rm K}}{{\rm T}_{\rm sub}} \right)^{2.8} {\rm pc}. \tag{14}$$

Within this region the opacity is dominated, at sufficiently high temperatures, by electron scattering opacity. This should be the case at the inner edge of the nuclear accretion disk.

I will therefore adopt the following model for opacities in what follows. I assume that dust opacity is dominant outside the sublimation region, and normalize to $\kappa = 100\kappa_{100} \, {\rm cm}^2 \, {\rm gm}^{-1}$ in order to evaluate the balance between AGN luminosity and outflow with protogalactic accretion rate, and electron scattering opacity within. I use the former to compute the momentum balance at large radii, typically a few kpc, and the latter to evaluate the Eddington luminosity associated with a specified mass accretion rate onto the black hole, typically at 0.1 pc or less.

3.3. Gas Disk

To proceed further, we need to evaluate the gas surface density. Let us assume a disk geometry for the gas, following the discussion of Thompson et al. (2005). The disk structure is determined by

$$\Sigma_{\rm gas} = 2\rho_{d,{\rm gas}}h, \quad p_{d,{\rm gas}} = \rho_{d,{\rm gas}}\sigma_d^2,$$
$$\Sigma_d = \frac{\sigma^2}{\pi G R}, \quad \Omega^2 = GM_d/R^3, \tag{15}$$

where $h = \sigma_d/\Omega$ is the disk scale height, σ_d is the gas velocity dispersion, and the spheroid velocity dispersion is $\sigma = \sqrt{2}\Omega R$.

We assume that the gas disk, embedded in the spheroid, is massive enough to be self-gravitating and maintains itself in a state of marginal gravitational instability, so that the Toomre parameter $Q \sim 1$. The inner disk will be stable because of AGN heating. High-resolution observations of nearby AGNs (Sani et al. 2012) indeed suggest that the thick disk observed on ~ 100 pc scales is stable to star formation ($\sigma_d = 20$–40 km s^{-1} and $Q > 1$).

The outer disk instability, where cooling is significant, is set by

$$Q = \frac{\kappa_\Omega \sigma_d}{\pi G \Sigma_{\rm gas}}, \quad {\rm with} \ \Sigma_{\rm gas} = \frac{2\Omega\sigma_d}{\pi G Q}, \tag{16}$$

where $\kappa_\Omega = \sqrt{4\Omega^2 + d\Omega^2/d\ln r}$ is the epicyclic frequency.

The disk stellar and gas surface densities (identifying M_* with M_d) are

$$\Sigma_* = \frac{\sigma^4}{\pi G^2 M_*} \ {\rm and} \ \Sigma_{\rm gas} = \frac{\sigma^3 \sigma_d}{\sqrt{2}\pi Q G^2 M_*}. \tag{17}$$

Hence the gas fraction is

$$f_g = \frac{\sigma_d}{\sqrt{2}Q\sigma}. \tag{18}$$

To avoid a detailed radiative transfer model, we adopt a more global approach. In particular, to compute emission characteristics, we will need to evaluate the radial temperature profile. This is beyond the scope of this paper. For generality, however, we give some key equations that, in particular, highlight the role of the opacity which is used elsewhere in this study in connection with the Eddington luminosity.

To infer the emission properties, we need to evaluate the temperature and density in the star-forming region. If the outer disk radiates predominantly by dust emission, one can compute the dust temperature by setting

$$2\tau_\kappa \sigma_{\rm SB} T_{\rm dust}^4 = \epsilon_{\rm rad} c^2 \dot{\Sigma}_*, \tag{19}$$

where $\epsilon_{\rm rad} \sim 0.001$ is the ratio of radiation per unit mass of newly formed stars for a typical initial mass function (IMF). I require the dust optical depth to be of order unity.

Based on the dust emissivity ($\propto \nu^\beta$) fit to the mean spectral energy distribution of quasar hosts in the redshift range $1.8 < z < 6.4$ (Beelen et al. 2006), I adopt $\beta \approx 1.6$, and I find the dust disk temperature in the optically thin regime from the preceding model to be

$$T_d^{\rm disk} = T_0 \left(\frac{\epsilon_{\rm rad} \epsilon_{\rm SN} c^2}{2\kappa_0 t_{\rm dyn} \sigma_{\rm SB} T_0^4} \right)^{\frac{1}{4+\beta}}$$
$$= 33 \text{ K} \left(\frac{\epsilon_{r,-3} \epsilon_{\rm SN,0.02}}{t_{d,7} \kappa_{2.4}} \right)^{0.18}, \tag{20}$$

in reasonable agreement with the data for disks of normal star-forming galaxies. Here, $\epsilon_{\rm SN} = 0.02\epsilon_{\rm SN,0.02}$, $\epsilon_{\rm rad} = 0.001\epsilon_{r,-3}$, $t_{\rm dyn} = 10^7 t_{d,7}$ yr $= 2.10^7$ yr $R_{\rm kpc}^{1/2} \Sigma_{d,100}^{-1/2}$, $\kappa = 2.4\kappa_{2.4}$ cm^2 gm^{-1} at 100 K, $R_d = R_{\rm kpc}$ kpc, and $\Sigma_d = 100\Sigma_{d,100}$ $M_\odot$ pc^{-2}. Additional heating will come from the AGN-triggered star formation as discussed below, so that quasar host galaxies will be warmer.

3.4. AGN Self-regulation

We now assume that AGN self-regulation controls the gas reservoir and hence the size of the star-forming disk. In reality, it is the innermost disk that is primarily affected, and we assume that in this region the rotation curve approximates that of a rigid body. This is of course appropriate for the spheroidal stellar distribution that is produced as a consequence of the jet-driven bow shock that drives turbulent compression of gas clouds and star formation. The gas velocity dispersion is increased as a consequence of the jet interaction.

The region where AGN feedback can be positive is determined by the condition that the AGN-induced pressure exceeds the dynamical pressure that controls the ambient ISM. Numerical simulations demonstrate that enhanced AGN-driven pressure from jet backflow indeed compresses the disk gas and enhances star formation (Gaibler et al. 2012). The result is not surprising despite the apparent mismatch in timescales between AGN pressure pulses and star formation because it is the local star formation timescale in overpressured dense gas clumps that is relevant rather than the global disk timescale. The dynamical pressure is

$$p_{\rm dyn} = \pi G f_g \Sigma_d^2, \tag{21}$$

and the AGN-induced pressure is

$$p_{\rm AGN} = f_{pE} \frac{L_E}{4\pi r^2 c} = f_{pE} \frac{G M_{\rm BH}}{\kappa r^2}. \tag{22}$$

Note that here f_g is a function of radius, whereas in the expression that we use for the black hole mass,

$$M_{\rm BH} = \bar{f}_g \frac{\kappa \sigma^4}{4\pi G^2} = \frac{\kappa}{4} \bar{f}_g \pi R_d^2 \Sigma_d^2, \tag{23}$$

the gas fraction is computed from near-zone momentum balance and is the mean value for the galaxy. Here I have used the disk relation $\Sigma_d = \sigma^2/(\pi G R_d)$, and find that the pressure ratio reduces to

$$\frac{p_{\rm AGN}}{p_{\rm dyn}} = f_{pE} \frac{M_{\rm BH}}{\kappa \pi r^2 f_g \Sigma_d^2} = \frac{f_{pE} \bar{f}_g}{4 f_g} \left(\frac{R_d}{r} \right)^2 \tag{24}$$

in the gas-rich inner disk. Moreover, the dynamical pressure as estimated above most likely overestimates the true ISM pressure. I conclude that AGN-induced pressure is likely to play an important role in regulating star formation in the inner disk on kpc scales. At smaller radii, AGN pressure dominates.

3.5. Bulge Formation

I evaluate the radius within which AGN-induced pressure dominates. I refer to this scale as the (proto)bulge radius, R_b, which I identify in order of magnitude with the disk scale length R_d, my assumption being that the newly formed stars within R_d form the bulge. In subsequent numerical examples, I take $R_b \approx 0.1\,R_d$ as an estimate. The resulting stellar bulge could form by satellite infall, disk secular instability, or, as argued below, by AGN-induced outflows and star formation.

Note that high-redshift compact quiescent galaxies may indeed contain disks (Chevance et al. 2012). The effective radius of star-forming galaxies observed at high redshift (Mosleh et al. 2012) is comparable to that of classic bulges, as well as to the scales inferred for the predecessors of compact quiescent galaxies at lower redshift (Barro et al. 2013).

3.6. Positive Feedback: AGN-driven Star Formation

My basic hypothesis is that AGNs can have positive as well as negative feedback on star formation rates. The observational consensus is mixed. Certainly, radio-jet-induced triggering does occur, both of star formation rates (Croft et al. 2006) and of molecular gas formation (Feain et al. 2007). Quenching of star formation is established for nearby active galaxies (Schawinski et al. 2007).

However, recent surveys find little evidence that X-ray luminous AGNs quench star formation (Harrison et al. 2012) and indeed that optically selected radio-loud QSOs have enhanced star formation at lower luminosities (Kalfountzou et al. 2012). The latter result raises the question of why such an effect is not seen at high radio power. One could speculate as follows. The relevance of high Eddington luminosity to positive feedback is observationally elusive. It might be that at low Eddington luminosities, mechanical feedback is dominant, in which case this would plausibly be the major source of positive feedback. A testable prediction is that evidence for enhanced outflows should be especially prominent in positive feedback candidates, targeted by elevated SSFR at high redshift.

In what follows, I will assume that enhanced pressure associated with the central AGN enhances star formation. This effect may be more prominent at lower luminosities as the starburst is likely to saturate at high luminosity, in part due to induced strong outflows. These are observed to be initiated at high pressures and associated mass loading (Newman et al. 2012).

The AGN pressure-driven star formation rate is

$$\dot{\Sigma}_*^{\rm AGN} = \frac{\epsilon_{\rm SN}}{\sigma_d} \Sigma_{\rm gas} \sqrt{\frac{\pi G p_{\rm AGN}}{f_g}} = \frac{\epsilon_{\rm SN}}{\sigma_d} \Sigma_{\rm gas} G \sqrt{\frac{\pi f_{pE} M_{\rm BH}}{\kappa f_g r^2}}. \tag{25}$$

This yields a Schmidt–Kennicutt-like law at a given ratio of black hole to spheroid mass:

$$\dot{\Sigma}_*^{\text{AGN}} = G\Sigma_{\text{gas}}^{3/2} \frac{\pi \epsilon_{\text{SN}}}{f_g \sigma_d} \left(\frac{M_{\text{BH}}}{M_*}\right)^{1/2} \left(\frac{f_{pE}}{\kappa}\right)^{1/2}. \quad (26)$$

If $\tau = \kappa \Sigma_{\text{gas}}/2$ is specified, one can rewrite this as

$$\dot{\Sigma}_*^{\text{AGN}} = \frac{\Sigma_*}{\tau_S} \zeta (\tau/2)^{1/2} f_{pE}^{1/2} \left(\frac{M_{\text{BH}}}{M_*}\right)^{1/2}, \quad (27)$$

where

$$\zeta = \frac{\epsilon_{\text{SN}} c}{2\sigma_d} = \frac{m_{\text{SN}} v_c c}{2 E_{\text{SN}}}$$

and

$$\tau_S = c\kappa (4\pi G)^{-1}.$$

The corresponding specific star formation rate is

$$\text{SSFR} = \frac{\zeta}{\tau_S} \sqrt{\frac{\tau f_{pE}}{2} \frac{M_{\text{BH}}}{M_*}}. \quad (28)$$

I set

$$\dot{M}_{\text{BH}} = 4\pi \frac{G M_{\text{BH}}}{c\eta\kappa} = M_{\text{BH}}/t_{\text{BH}},$$

where the black hole e-folding growth time

$$t_{\text{BH}} = \eta\tau_S \equiv c\eta\kappa (4\pi G)^{-1} = 4.3 \times 10^7 \eta_{0.1} \text{ yr}$$

is equal to the so-called Salpeter time and I define $\tau_S = c\kappa (4\pi G)^{-1} \equiv 4.3 \times 10^8$ yr as a reference time (the Salpeter time at 100% efficiency). The numerical values assume electron scattering opacity and $\eta \equiv 0.1\eta_{0.1}$. I note that

$$\frac{m_{\text{SN}} v_c c}{E_{\text{SN}}} = 360 \frac{m_{\text{SN},150} v_{c,400}}{E_{51}}$$

and

$$\zeta = 180 \frac{m_{\text{SN},150} v_{c,400}}{E_{51}}. \quad (29)$$

To infer the disk-averaged SSFR, let $\tau = \bar{\tau} = (f_{pE}/2)(M_{\text{BH}}/M_*)$ at $r = R_d$. The SSFR is given by

$$\text{SSFR} = \frac{\zeta}{\tau_S} \frac{M_{\text{BH}}}{M_*} \frac{f_{pE}}{2} \quad (30)$$

$$\sim \frac{3}{\tau_S} \zeta_{200} \frac{M_{\text{BH}}}{10^{-3} M_*} f_{pE,30} \quad (31)$$

$$\sim (10^8 \text{ yr})^{-1}, \quad (32)$$

since $M_{\text{BH}} \sim 10^{-3} M_*$, where $\zeta = 200\zeta_{200}$ and $f_{pE} = 30 f_{pE,30}$. This is similar to what is observed at $z \gtrsim 2$ (Weinmann et al. 2011; Bouwens et al. 2012; Stark et al. 2013). The ratio of stellar luminosity to mass is

$$\frac{L_*^{\text{AGN}}}{M_*} = \epsilon_{\text{rad}} c^2 (\text{SSFR}) \approx \frac{2 \times 10^{17} \text{ s}}{t_{\text{BH}}} \text{ erg g}^{-1} \text{ s}^{-1} \approx 200 \frac{M_\odot}{L_\odot}, \quad (33)$$

and agrees with ultraluminous infrared galaxy (ULIRG) observations (Scoville 2003), although possibly requiring a slightly top-heavy IMF (with $\epsilon_{\text{rad}} \sim 2 \times 10^{-3}$).

We now have the following equation for the AGN-induced star formation rate in terms of the black hole growth rate:

$$\dot{M}_*^{\text{AGN}} = \zeta \frac{M_{\text{BH}}}{\tau_S} \sqrt{\frac{\tau f_{pE}}{2} \frac{M_*}{M_{\text{BH}}}} = \frac{\eta\zeta}{2} f_{pE} \dot{M}_{\text{BH}} \frac{R_d}{r}. \quad (34)$$

I note that

$$\frac{\dot{M}_*^{\text{AGN}}}{\dot{M}_{\text{BH}}} = \frac{\eta\zeta f_{pE}}{2} \frac{R_d}{r}. \quad (35)$$

This ratio (~ 600) is similar to what is observed for stacked AGNs at $z \sim 2$, if I set $r \sim 0.5 R_d$ and $f_{pE} \sim 30$ (Mullaney et al. 2012).

The dust temperature is dominated by the inner disk,

$$T_d^{\text{AGN}} = T_d^{\text{disk}} \left(\frac{p_{\text{AGN}}}{p_{\text{dyn}}}\right)^{\frac{1}{2(4+\beta)}} = T_d^{\text{disk}} \left(\frac{R_d}{r}\right)^{\frac{3}{4(4+\beta)}}. \quad (36)$$

The enhanced dust temperatures (~ 45K) correspond to those observed for AGNs, evaluated at $r \sim 0.1 R_d$ or ~ 100 pc.

3.7. Gas Accretion and Star Formation Rate

The ratio of black hole growth to stellar mass growth timescales can be written as

$$\text{SSFR} \cdot t_{\text{BH}} = \frac{\eta\zeta f_{pE}}{2} \frac{M_{\text{BH}}}{M_*} \left(\frac{R_d}{2r}\right)$$

$$\approx 0.3\eta_{0.1} \zeta_{200} \left(\frac{10^3 M_{\text{BH}}}{M_*}\right). \quad (37)$$

The stellar mass grows over a similar timescale as that of the black hole: our model couples stellar mass growth and black hole growth. Note however that the model does not provide a duty cycle: it does not distinguish between a single period of sustained growth or many shorter periods.

Evidence for an exponentially rising burst of star formation may arise in the form of the flattening or blueing of rest-frame UV continuum slopes of star-forming galaxies at high redshift ($z \sim 4$ for LBGs; Jones et al. 2013). Another possible indicator comes from the frequency of starburst galaxies at $z \sim 2$: these only represent a significant fraction (of order 50%) of the SFR main sequence if the starburst timescale is as short as ~ 20 Myr rather than the customarily adopted ~ 100 Myr (Rodighiero et al. 2011).

Dwarf galaxies undergo short, intense starbursts on similar short timescales (Weisz et al. 2012). If these episodes were AGN-induced, it has been suggested that outflows from intermediate-mass black holes may be responsible for ejecting a substantial fraction of baryons from the dwarfs (Silk & Nusser 2010), something that supernova feedback seemingly fails to accomplish (Powell et al. 2011; Peirani et al. 2012).

I now make use of $f_g = \bar{f}_g (R_d/r)^{1/2}$ and integrate the star formation rate induced by AGNs, expressed as

$$\dot{M}_*^{\text{AGN}} = \frac{\eta\zeta}{2} f_{pE} \dot{M}_{\text{BH}} \frac{R_d}{r} = \frac{\eta\zeta}{2} f_{pE} \dot{M}_{\text{BH}} (f_g/\bar{f}_g)^2 \quad (38)$$

for the redshift dependence of three different gas supply models. The models are:

1. constant gas fraction as observed at high redshift in star-forming galaxies (Bothwell et al. 2013), discussed above, so that $\rho_g(r) \propto \rho_*(r)$,
2. closed box ($M_g + M_* =$ constant) as might be appropriate for a major merger-induced gas supply,
3. cosmological accretion ($M_g = M_{g,0}(1 + z)^\gamma$) along cold filaments as favored by cosmological simulations. Here $\gamma \approx 2.2$ and $\dot{M}_g \propto t^{-\alpha}$ with $\alpha \approx 5/3$ for LCDM (Neistein & Dekel 2008). I neglect gas sinks due to star formation and outflows, as justified by Bouché et al. (2010).

We infer for all of these models that the stellar mass undergoes exponentially rapid growth on a timescale of order the black hole growth timescale, since the exponential term dominates all solutions for M_*.

3.7.1. Constant Gas Fraction

At constant f_g (case 1), the stellar mass integrates to

$$M_*^{\mathrm{AGN}} = \eta\zeta f_{pE}(f_g/\bar{f}_g)^2 \, M_{\mathrm{BH}}$$
$$= 3000\eta_{0.1}\zeta_{200}f_{pE,30}(f_{g,0.5}/\bar{f}_{g,0.2})^2 \, M_{\mathrm{BH}}. \quad (39)$$

The ratio of star formation to black hole growth rates is approximately equal to the ratio of stellar mass to black hole mass produced during the coeval growth phases. Both the stellar mass in the starburst and the star formation rate increase exponentially on the black hole growth timescale.

3.7.2. Closed Box

In the closed box model, case (2), I define $M_0 = M_g + M_*$, $\mu = M_*/M_0$, and $f_g = M_g/M_*$. The star formation rate is

$$\dot{M}_*^{\mathrm{AGN}} = \frac{\eta\zeta}{2}\dot{M}_{\mathrm{BH}}f_{pE}(f_g/\bar{f}_g)^2 \quad (40)$$

$$= \eta\zeta\dot{M}_{\mathrm{BH}}f_{pE}/\bar{f}_g^2(\mu^{-1} - 1)^2. \quad (41)$$

The solution is

$$\frac{M_{\mathrm{BH}}}{M_*} = \frac{2}{\eta\zeta f_{pE}}\frac{1}{\mu}\left[\mu - 1 + \frac{1}{1-\mu} + 2\ln(1-\mu)\right]. \quad (42)$$

In the early, gas-rich limit, this reduces to

$$\frac{M_{\mathrm{BH}}}{M_{\mathrm{gas}}} = \frac{2}{\eta\zeta f_{pE}}\frac{f_g^2}{3}. \quad (43)$$

In the late, gas-poor limit, we have

$$\frac{M_{\mathrm{BH}}}{M_*} = \frac{2}{\eta\zeta f_{pE}}f_g = 0.001\eta_{0.1}^{-1}\zeta_{200}^{-1}f_{pE,30}^{-1}\bar{f}g, 0.3. \quad (44)$$

Here I denote the current epoch gas fraction ($f_{g,0}$) with $\bar{f}_g$.

3.7.3. Accretion

In the accretion model, case (3), the star formation rate is

$$\dot{M}_*^{\mathrm{AGN}} = \frac{\eta\zeta}{2}f_{pE}\dot{M}_{\mathrm{BH}}f_{g,0}/\bar{f}_g(t_0/t)^{2\alpha}. \quad (45)$$

This integrates to (t_0 is the Hubble time)

$$\frac{M_*}{M_{\mathrm{BH}}} = \frac{\eta\zeta}{\alpha}f_{pE}\,(t_0/t_{\mathrm{BH}})^{2\alpha}g(t), \quad (46)$$

where $x = t/t_{\mathrm{BH}}$ and $g(x)$ is a weakly varying function (of time)

$$g(x) = e^{-x}\int e^x x^{-2\alpha}dx.$$

In all cases, the ratio of black hole to bulge mass is approximately equal to the instantaneous ratio of black hole accretion rate to star formation rate and of order

$$2(\eta\zeta f_{pE})^{-1}(\bar{f}_g/f_g)^2 \sim 0.001$$

for typical parameter choices ($\eta \sim 0.1$, $f_{pE} \sim 30$, $\bar{f}_g = 0.2$, $f_g \sim 0.4$, $m_{\mathrm{SN},150} \sim v_{400} \sim E_{51} \sim 1$).

3.8. AGN-driven Outflows

Black hole growth is generically expected to generate outflows. The outflow rate is given by

$$\dot{M}_w = f_p\frac{\eta}{v_w c}L_{\mathrm{AGN}} = f_{pE}\frac{c}{v_w}\dot{M}_{\mathrm{BH}} \quad (47)$$

$$= 1000f_{pE,30}v_{w,10^4}^{-1}\dot{M}_{\mathrm{BH}} \quad (48)$$

since $L_{\mathrm{AGN}} = f_E\eta c^2\dot{M}_E$. Here, the initial wind velocity $v_w = 10^4 v_{w,10^4}$ km s^{-1}. Incorporating the approximate dependence of the momentum advantage factor f_p on v_w as discussed above, one infers that $\dot{M}_w \overset{\propto}{\sim} L_{\mathrm{AGN}}\,v_w^{-11/6}$. Simulations show that observed outflow velocities match this prediction (Wagner et al. 2012).

One can now express the outflow rate in terms of the star formation rate:

$$\dot{M}_w = 2\frac{c}{v_w}\frac{1}{\eta\zeta}(\bar{f}_g/f_g)^2\dot{M}_*^{\mathrm{AGN}}. \quad (49)$$

Hence the ratio of outflow to star formation rate is

$$\frac{\dot{M}_w}{\dot{M}_*^{\mathrm{AGN}}} = 2\frac{c}{v_w}\frac{1}{\eta\zeta}(\bar{f}_g/f_g)^2 = \frac{0.75}{\eta_{0.1}\zeta_{200}v_{w,10^4}}\left(\frac{\bar{f}_{g,0.2}}{f_{g,0.4}}\right)^2. \quad (50)$$

Even in the most massive galaxies, the outflow rate can be of order the star formation rate, due to the role of the AGN.

Empirically, there is a generic coupling for AGNs between star formation rate and outflow rate, e.g., as found for the well-resolved case of Mrk 231 (Rupke & Veilleux 2011). This coupling is also true for star-forming galaxies without strong AGNs (Bouché et al. 2012). However, the difference in the latter case is that the outflow velocities are of order the circular velocities and well below the escape velocities. This result suggests that supernova-driven outflows drive gas circulation in the halo but cannot eject significant amounts of baryons from the galaxy potential wells. On the other hand, the outflow velocities associated with luminous AGNs generally exceed the escape velocity of the host galaxy.

4. SUMMARY AND DISCUSSION

Triggered star formation is not a new concept. It is well studied in the galactic context for triggering by massive star H II regions, first introduced by Elmegreen & Lada (1977), and widely explored on galactic scales. Triggering of massive star cluster formation commonly occurs in galaxy mergers (Whitmore et al. 2010). For AGNs, however, the idea is somewhat new and has attracted increasing interest in view

of the complex and hitherto obscure interaction between AGNs and star formation.

Major mergers are often blamed for both enhanced AGN activity and star formation. There is an active ongoing debate however; for example, it has been argued that new-born spheroids are not the product of major mergers (Kaviraj et al. 2013), nor is enhanced star formation in massive galaxies at $z \sim 0.6$ primarily due to interactions (Robaina et al. 2009). There is a general consensus, however, that while major mergers are nevertheless important for the most extreme star formation rates observed at high redshift, and are important locally in accounting for ULIRGs, they are likely subdominant at high redshift both in triggering the bulk of star formation (Kartaltepe et al. 2012) and in triggering AGNs (Treister et al. 2012).

One alternative to mergers is gas accretion triggering. But for the formation of early-type galaxies, accretion is generically filamentary according to numerical simulations, e.g., Sales et al. (2012). However, observations reveal quasi-spherical star-formation-induced gas excitation around radio-quiet AGNs (Liu et al. 2013b). This is suggestive of AGN triggering by quasi-spherical winds from AGNs rather than by accretion flows.

While I have focused here on radio jet-driven bubbles, being guided by the results from recent numerical simulations, much of this discussion is applicable to the radio-quiet mode, where quasar-driven winds provide similar feedback. Indeed, a recent numerical study confirms the similarity between jet and wind-induced outflows (Wagner et al. 2013), with corresponding implications for pressure enhancements and (presumably) triggered star formation according to the scheme developed in Gaibler et al. (2012). A possible example of a QSO-wind-induced triggering of a young galaxy at $z = 3.045$ is given by Rauch et al. (2013).

In summary, I have argued that AGN triggering of star formation arises via AGN pressure regulation. This allows inclusion of AGN-induced pressure into what is essentially a reinterpretation of the usual star formation law, by introducing jets and/or winds into an inhomogeneous ISM, and leads to enhanced star formation rates.

Three possibilities are considered for the evolution of the gas fraction: a constant gas fraction (for illustrative purposes), the more realistic cases of a closed box model (applicable in the case of a major merger), and an accretion merger (relevant for minor mergers or filamentary accretion of cold gas). The latter case is favored if indeed a significant fraction of SMBH growth occurs predominantly in disks (Schawinski et al. 2012).

Simple expressions are derived that relate black hole growth, star formation, and outflow rates. The SSFR is found to be essentially identical to the specific black hole accretion rate. Since the latter must be on the order of 3.10^{-8} yr^{-1} in order to grow SMBHs by $z \sim 7$ (as reviewed recently by Volonteri 2012), this means that starburst timescales are typically a few tens of millions of years rather than the normally adopted $\sim 10^8$ yr.

One consequence is that starbursts are a major contributor to star formation and are predicted to lie above the galaxy main sequence, as observed by *Herschel* at $z = 1.5$–2.5 (Rodighiero et al. 2011). The black hole mass is found to be around 0.001 of the old (spheroid) stellar mass. The black hole accretion rate is a similar fraction of the star formation rate, and predicted to be a factor of two or so higher, i.e., ~ 0.002, in the filamentary gas accretion model, as inferred when stacking X-ray-selected samples of ultraluminous AGNs at high redshift (Mullaney et al. 2012).

The ratios of black hole to spheroid mass and of the comoving black hole accretion rate density to star formation rate density are found to track each other as a function of time, although offset by ~ 1000. This is well known at low redshift (Silverman et al. 2009), but the present model predicts that a similar offset continues at high redshift.

Indeed, allowance for the prevalence of buried luminous AGNs (Imanishi et al. 2010; Treister et al. 2011) flattens the observed black hole accretion rate density at high redshift. Allowance for lack of dust at high redshift ($z \sim 4$–7 from Bouwens et al. 2012), and especially top-down galaxy formation (Behroozi et al. 2013), lowers the star formation rate density at high redshift. I conclude that the shapes of the two rates may well be similar over $z = 0$–6, but offset by a factor of order 1000.

Both black hole and star formation rates are exponentially increasing functions of time. This lowers the mean age of luminous starbursts and should lead to flatter UV continua than in any unaccelerated burst, as would be the case in the absence of positive AGN feedback. Systematically flatter rest-frame UV are indeed observed at $z \sim 4$ (Jones et al. 2013).

Exponentially increasing star formation rates are also found in certain wind-regulated hydrodynamic models and are a consequence of high cold gas accretion rates at early epochs (Finlator et al. 2011). These models give a wide range of fits to the SSFR (Davé et al. 2011; de Barros et al. 2012). However, the rate of early cold accretion in massive galaxies may be severely overestimated according to more realistic, moving mesh hydrodynamic simulations (Nelson et al. 2013). The models advocated here provide an alternative means of obtaining rapidly rising star formation rates.

The exponential star formation rate self-limits the period of black hole growth, since the gas reservoir will be depleted. The limiting star density in the starburst is found empirically to be of order (Hopkins et al. 2010) 10^{11} $M_\odot$ kpc^{-2}. To attain such a high value, one might need black hole growth, as well as spheroid growth, to occur via a series of short bursts with a duty cycle of order 10% over a period of perhaps a Gyr. These latter parameters, not calculated here but the subject of future work, are likely related to the radiative efficiency of mass accretion onto the black hole.

With regard to massive galaxies, the problem with the inability of a single mode of star formation to reproduce the mass function of galaxies at both low and high redshift is well known. Models that fit the high-redshift mass function fail at low z (Henriques et al. 2011), and models that fit at low z fail at high z (Fontanot et al. 2009), especially for the most massive galaxies (Mutch et al. 2012).

There is a strong case for introducing a second mode of star formation that provides higher efficiency, in particular at high redshift. Whether this is due to tweaking the conventional density threshold and Schmidt–Kennicutt law approach, for example, by appealing to enhanced gas accretion as might be supplied in mergers (Khochfar & Silk 2011), or by introducing new physics associated with positive feedback from AGNs, as advocated here, is yet to be determined.

Finally, I make several speculative suggestions for possible observational tests of positive feedback by AGNs.

1. It is clear that high-resolution observations of massive young galaxies and of molecular gas at high redshift will help elucidate these issues. One target would be the enhanced star formation and turbulence induced at the edges of cloud complexes. This is seen on cloud scales in nearby

star-forming clouds (Dirienzo et al. 2012). With ALMA or GMT/TMT/ELT resolution, it would be interesting to extend such studies to the massive star-forming clumps seen in redshift $z \sim 2$ galaxies, which include extremely high star formation densities (Menéndez-Delmestre et al. 2013).

2. One specific example is the quasar host galaxy (Walter et al. 2009), and another is a galaxy at $z = 6.34$ with the most extreme star formation rate surface density yet recorded (Riechers et al. 2013). These so-called hyper-starbursts at high redshift provide sites where evidence of an AGN trigger might be sought.

3. A class of objects where positive feedback is inferred and further evidence could be sought for evidence of mechanical driving is that of AGNs in the early universe with enhanced FIR emission lines ([C II], [O III]) from photodissociation regions on the surfaces of molecular clouds. These observations are indicative of localized (kpc-scale) intense star formation bursts (Stacey et al. 2010).

4. Formation of dense molecular clouds is a crucial step in the triggering pathway. One manifestation would be strong shocks and enhanced molecular cooling in molecules such as H_2O, which is found to be exceptionally strong in high-redshift star-forming galaxies (Omont et al. 2013). With larger samples, a correlation could be sought between H_2O emission and AGN activity. I note that a lack of correlation is reported for polycyclic aromatic hydrocarbon emission (Rawlings et al. 2013), but the shorter lived phase of intense molecular cooling is a more robust diagnostic of cloud formation and compression, the necessary prerequisites for star formation.

5. The enhancement of star formation in the presence of an AGN is accepted, as is the occurrence of strong outflows. However, any causal link is yet to be established. Stellar populations are found to be older in AGN hosts at $z < 1$ (Vitale et al. 2013). This extends previous work on similar age offsets at $z \lesssim 0.1$ (Schawinski et al. 2007). There is evidence for bimodal stellar populations in luminous radio galaxies at high redshift, suggesting that a massive starburst associated with the onset of radioactivity may have occurred (Rocca-Volmerange et al. 2013). It would be interesting to see if stellar population age in AGN hosts were correlated with stellar mass and hence SMBH mass, as triggering might suggest. This is because the strength of feedback, as characterized by the Eddington ratio, increases with increasing SMBH mass.

6. It now appears that the comoving AGN accretion rate density tracks the cosmic star formation history, although reduced in mass flux by a factor $\sim$1000, once allowance is made for galaxy luminosity downsizing and the frequency of buried AGNs. This result needs to be verified with larger samples of AGNs and statistical differences sought between the low-redshift sample ($z \lesssim 2$), where star formation declines with time, and the high-redshift sample ($z \gtrsim 2$), where star formation increases with time. The present model leads one to expect that quenching dominates at low z and triggering at high z. This is a natural consequence of the present model: early positive feedback is followed by a phase of negative feedback. This is difficult to prove for individual objects, especially if the positive feedback phase is both brief and buried. However, large samples observed in these respective redshift ranges might be expected to reveal systematic differences in star formation history and gas depletion timescales of the host galaxies.

7. The scatter in the correlation between black hole mass and spheroid velocity dispersion or spheroid mass could contain the imprint of AGN triggering. For example, one might expect the significance of triggering to correlate with Eddington ratio, in which case the residuals in stellar mass would correlate with Eddington ratio and with black hole growth.

8. Metallicities also provide a potential probe. The strong outflows associated with positive feedback will lead to early enrichment of the circumgalactic medium, with enhanced $[\alpha/Fe]$ as a possible chronometric signature. A time delay between AGN triggering and enrichment would be expected. Ejection from the galaxies of metal-enriched hypervelocity stars would survive as possible witness to these early events (cf. Silk et al. 2012).

9. Jet-induced triggering should result in rings of young stars, embedded in rings of compressed molecular gas. ALMA resolution should probe the morphology of the molecular gas. These rings may fragment to form star clusters: intriguingly, there is a possible example of a super-star cluster with a high velocity relative to the halo gas in a ULIRG (Rodríguez Zaurín et al. 2009). More realistic geometries might include chains of sequential star formation triggering.

10. A correlation has recently been reported between radio jet power and star formation rates in a sample of X-ray-selected AGNs (Zinn et al. 2013). Excess star formation is found for objects with radio jets, in contrast to the quenching inferred for X-ray AGNs, providing evidence for positive feedback. Since the massive outflows seen in many star-forming AGNs provide de facto evidence for star formation quenching, it would be especially interesting to see whether outflow rates anticorrelate with the claimed radio-enhanced star formation in the X-ray-selected AGN sample, as might be anticipated if a phase of positive feedback precedes quenching by outflows and winds.

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