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A simple model for AGN feedback in nearby early-type galaxies

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ABSTRACT
Recent work indicates that star-forming early-type galaxies residing in the blue cloud migrate rapidly to the red sequence within around a Gyr, passing through several phases of increasingly strong AGN activity in the process (Schawinski et al. 2007, MNRAS, 382, 1415; S07 hereafter). We show that natural depletion of the cold gas reservoir through star formation (i.e. in the absence of any feedback from the AGN) induces a blue-to-red reddening rate that is several factors lower than that observed in S07. This is because the gas depletion rate due to star formation alone is too slow, implying that another process needs to be invoked to remove cold gas from the system and accelerate the reddening rate. We develop a simple phenomenological model, in which a fraction of the AGN's luminosity couples to the gas reservoir over a certain 'feedback timescale' and removes part of the cold gas mass from the galaxy, while the remaining gas continues to contribute to star formation. We use the model to investigate scenarios which yield migration times consistent with the results of S07. We find that acceptable models have feedback timescales $\lesssim 0.2$ Gyrs. The mass fraction in young stars in the remnants is $\lesssim 5\%$ and the residual cold gas fractions are less than 0.6%, in good agreement with the recent literature. At least half of the initial cold gas reservoir is removed as the galaxies evolve from the blue cloud to the red sequence. If we restrict ourselves to feedback timescales similar to the typical duty cycles of local AGN (a few hundred Myrs) then a few tenths of a percent of the luminosity of an early-type Seyfert ($\sim 10^{11}$ $L_\odot$) must couple to the cold gas reservoir in order to produce migration times that are consistent with the observations.

Key words: galaxies: active galaxies: interactions galaxies: starburst galaxies: evolution galaxies: elliptical and lenticular, cD

1 INTRODUCTION

The development of the current generation of galaxy formation models has been inextricably linked to our understanding of the properties of early-type galaxies. Their red optical colours (e.g. Bower et al. 1992; Ellis et al. 1997; van Dokkum et al. 2000; Bernardi et al. 2003; Bell et al. 2004; Faber et al. 2007), high alpha-enhancement ratios (e.g. Thomas et al. 1999; Trager et al. 2000a,b; Thomas et al. 2005) and their obedience of a tight 'Fundamental Plane' (e.g. Jorgensen et al. 1996; Saglia et al. 1997; Forbes et al. 1998; Peebles 2002; Franx 1993, 1995; van Dokkum & Franx 1996) indicate that the bulk (>80%) of their constituent stellar mass forms at high redshift ($z > 1$). The star formation at late epochs (e.g. Trager et al. 2000a; Nelan et al. 2005; Graves et al. 2009a,b; Scott et al. 2009; van Dokkum et al. 2010), recently quantified using rest-frame UV/optical photometry (Ferreras & Silk 2000; Yi et al. 2005; Kaviraj et al. 2007; Schawinski et al. 2007; Jeong et al. 2007; Kaviraj 2008; Kaviraj et al. 2008; Jeong et al. 2009; Salim & Rich 2010), is plausibly driven by minor merging through the accretion of gas-rich satellites (Schweizer et al. 1990; Schweizer & Seitzer 1992; Kaviraj et al. 2009; Kaviraj 2010a,b, see also Tal et al. 2009; Bournaud et al. 2007; Bezanson et al. 2009; Naab et al. 2009; Serra & Oosterloo 2010; Hopkins et al. 2010; Schawinski et al. 2010). This is supported by evidence for kinematical decoupling of the (ionised) gas from the stars (e.g. Sarzi et al. 2006) and the fact that the gas and associated dust appears not to

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correlate with the stellar mass of the galaxy, irrespective of the local environment (e.g. van Dokkum & Franx 1995; Knapp & Rupen 1996; Combes et al. 2007). Both these trends indicate that the gas is, at least in part, external in origin.

While the characteristics of the early-type galaxy population have been exhaustively studied, the reproduction of those properties in the models remains problematic. A particular issue has been the continuing availability of cold gas and resultant star formation in massive galaxies (which are dominated by early-types) at late epochs, as supernova feedback becomes ineffective in very deep potential wells (see e.g. Dekel & Silk 1986; Benson et al. 2003). Strong gas cooling on to the central galaxies of groups and clusters leads to model galaxies being both too massive and too blue (e.g. Kauffmann et al. 1999; Somerville & Primack 1999; Cole et al. 2000; Murali et al. 2002; Benson et al. 2003), with alpha-enhancements that are too low to match the observed values (e.g. Thomas et al. 1999; Nagashima et al. 2005, but see Pipino et al. 2009). An additional source of energy is thus required to prevent cold gas from forming stars, either by supplementing the heating of the cold gas reservoir or, more plausibly, by removing a significant fraction of the cold gas mass from the potential well (e.g Martin 1999; Strickland & Stevens 2000).

Given the ubiquity of super-massive black holes (SMBHs) in local galaxies (e.g. Richstone et al. 1998) and the strong observed correlation between the masses of SMBHs and the luminosities/velocity dispersions of their host galaxy bulges (e.g. Magorrian et al. 1998; Gebhardt et al. 2000; Ferrarese & Merritt 2000; Tremaine et al. 2002; Häring & Rix 2004), it is likely that the evolution of galaxies is intimately linked to, or even regulated by, their central black holes (e.g Kauffmann & Heckman 2009; Netzer 2009). Consensus now favours Active Galactic Nuclei (AGN), powered by accretion of matter on to these central SMBHs, as a potential source of the 'missing' energy that is required to fulfil the feedback budget in massive galaxies (Silk & Rees 1998; Blandford 1999; Fabian 1999; Binney 2004; Silk 2005, but see also alternatives for imparting energy to the ambient gas in Birnboim et al. 2007; Khochfar & Ostriker 2008).

Several processes - e.g. radiative heating or kinetic energy input through jets (see the recent reviews by Begelman 2004; Fabian 2010) may contribute to the deposition of energy from the AGN into its ambient medium. In powerful AGN, jets inflate cocoons of relativistic plasma which are overpressured with respect to the surrounding gas, driving massive outflows (e.g. Begelman et al. 1984; Fabian et al. 2006). While an objection to invoking this mode of feedback to remove gas from the galaxy is the small volume-filling factor of the jets (e.g. Ostriker & Ciotti 2005), recent numerical simulations indicate a significant (and largely isotropic) interaction between the jet material and the multi-phase ISM (Antonuccio-Delogu & Silk 2008; Sutherland & Bicknell 2007). In any case, radiative pressure resulting from heating produces similar momentum-driven outflows (e.g. Ostriker et al. 2010) to those expected in jet-dominated systems. Theoretical arguments indicate that outflows are necessary in order to produce the observed correlations between SMBHs and their host galaxies (e.g. Ostriker et al. 2010). Coupled with observational evidence for the commonality of outflows in local AGN (e.g. de Kool 1997; Crenshaw & Kraemer 1999; Crenshaw et al. 2003; Everett 2007; Proga 2007) this suggests that a major facet of the feedback process is the injection of kinetic energy and removal of gas from the interstellar medium (ISM).

Although significant advances have been made in modelling the complex interaction of the AGN with the inter-stellar medium (e.g. Falle 1991; Kaiser & Alexander 1997; Kino & Kawakatu 2005; Alexander 2006; Krause & Alexander 2007; Antonuccio-Delogu & Silk 2008), the inclusion of AGN feedback in galaxy formation models remains largely phenomenological. Nevertheless, simple recipes for AGN feedback (e.g. Hatton et al. 2003; Granato et al. 2004; Kaviraj et al. 2005; Bower et al. 2006; Springel et al. 2005a; Croton et al. 2006; De Lucia et al. 2006; Schawinski et al. 2006; Khochfar & Silk 2006; Cattaneo et al. 2006, 2007; Di Matteo et al. 2007; De Lucia et al. 2007; Somerville et al. 2008; Rettura et al. 2010), have proved a valuable addition to the models, enabling good reproduction of local galaxy properties such as luminosity functions, the morphological mix of the Universe and the stellar populations of early-type galaxies. The trigger and intensity of feedback is postulated to vary with look-back time, with violent feedback from a 'quasar mode' truncating merger-driven star formation in the gas-rich Universe at high redshift (e.g. Springel et al. 2005b; Di Matteo et al. 2005), while a more quiescent 'maintenance mode' that probably operates in the gas-poor Universe at late epochs (e.g. Best et al. 2005, 2006; Schawinski et al. 2006, 2007; Khalatyan et al. 2008; Kormendy et al. 2009).

While energetic arguments make a compelling theoretical case for the need for AGN feedback, observational constraints on this feedback process *in the early-type population at late epochs* remain relatively limited but highly desirable. In a recent work, Schawinski et al. (2007, S07 hereafter) studied the potential impact of AGN on early-type evolution by exploring the recent star formation histories of ∼16,000 nearby ($0.05 < z < 0.1$) early-type galaxies in the field, as a function of the type of AGN activity present in these systems. The galaxies, drawn from the Sloan Digital Sky Survey (SDSS; Adelman-McCarthy et al. 2008), were selected through direct visual inspection of their SDSS images, which yields a more accurate morphological selection (e.g Kaviraj et al. 2007; Fukugita et al. 2007; Lintott et al. 2008) than methods based on colours or galaxy spectra. AGN diagnostics were performed using optical emission line ratios (Baldwin et al. 1981; Veilleux & Osterbrock 1987; Kauffmann et al. 2003; Miller et al. 2003; Kewley et al. 2006), separating the early-type population into galaxies that were 'star-forming', 'composites' (which have signatures of both AGN and star formation), 'Seyferts', 'LINERs' and 'quiescent' systems. The recent star formation history in each galaxy was quantified by fitting Lick absorption indices and multi-wavelength photometry in the ultraviolet (UV), optical and near-infrared (NIR) wavelengths (from the GALEX (Martin et al. 2005), SDSS and 2MASS (Skrutskie et al. 2006) surveys respectively) to a large library of model star formation histories. The model library was constructed using two bursts of star formation, the first fixed at high redshift (since the bulk of the mass in early-types is known to form at large look-back times), with the second allowed to vary in age and mass fraction. Realistic values of dust and metallicity were employed and the age and mass fraction of the second burst (which characterises the recent star formation episode) were calculated for each galaxy by fitting to the spectro-photometric data. S07 used their estimates of the recent star formation as a 'clock' to follow the migration of early-type galaxies from the red sequence to the blue cloud and explore the AGN classes that galaxies passed through in the course of that migration.

The S07 results strongly suggest that star-forming early-types residing in the blue cloud migrate rapidly to the red sequence within $\sim$ a Gyr, passing through several phases of increasingly strong AGN activity in the process. The AGN activity reaches its peak around 0.5 Gyrs (see also Wild et al. 2010). The 'reddening sequence' begins with the star-forming early-types which are, on average, the bluest population, followed by the composites, Seyferts, LINERs and quiescents in that order (see also Salim et al. 2007, who found similar results). The mass fraction in young stars remains similar along this sequence, while the age of the recent star formation progressively increases. Furthermore, mm-wavelength observations, from the IRAM 30m telescope, of a subset of the S07 early-type galaxy sample indicates that the cold molecular gas mass drops precipitously by an order of magnitude between the star-forming and LINER phases (Schawinski et al. 2009, S09 hereafter). Given the *coincidence* of rising AGN activity, the rapid observed evolution in colours and simultaneous fast removal of the molecular gas mass, it is reasonable to suggest that the AGN may play a significant role in the migration of early-types from the blue cloud to the red sequence. At this point, it is useful to note the characteristics of the feedback that might operate in these nearby early-type galaxies. Recent studies indicate that the trigger for the weak star formation observed in nearby early-type systems are gas-rich minor mergers (see e.g. Kaviraj 2010a,b). The feedback envisaged here is in the form of a jet-driven outflow which acts on the gas in the galaxy and may quench the star formation. Since the supply of gas in such minor mergers is relatively small, this outflow-driven feedback is likely to be much weaker than the violent 'quasar-mode' feedback (e.g. Springel et al. 2005a) that operates in gas-rich major mergers, that plausibly drive the quasar population at high redshift.

A robust conclusion about the role of the putative AGN feedback in the S07 early-types can only be achieved by comparing the observed colour transition to what might be expected in the absence of feedback on the system. If feedback was then found to be necessary, then the optical and mm-wavelength data presented in S07 and S09 offer an ideal dataset with which the broad characteristics of the coupling between the AGN and the cold gas reservoir in the host early-type galaxy can be characterised and properties of the feedback constrained. Note that, throughout this paper, we always refer to the gas mass contained in the molecular i.e. cold phase, hosted in a disk.

We begin, in Section 2, by demonstrating that, in the absence of AGN feedback, the expected blue-to-red colour transition and associated gas depletion in the star-forming early-types is likely to be much slower than that observed by S07. Proceeding under the assumption that these processes are accelerated by AGN feedback, we then construct a simple model, in Section 3, that describes the coupling between the AGN and the host galaxy's cold gas reservoir. In Section 4 we apply this model to a typical star-forming early-type in the blue cloud and explore scenarios which simultaneously reproduce the recent star formation observed in local early-type galaxies, the migration times observed by S07 and the gas depletion history presented in S09. We use these scenarios to draw general conclusions about the broad characteristics of the feedback from the central AGN, in particular the fraction of AGN energy that must couple to the cold gas reservoir and the timescale over which it does so. The novelty of this analysis is that the model is strongly constrained by these observational results. Finally, in Section 5, we summarise our findings and connect our results to recent observational work on recent star formation in early-type galaxies. The overall aim of this paper is to add an understanding of the role of AGN feedback to the developing picture of recent star formation in early-types at late epochs, and provide observationally-driven constraints on the 'maintenance mode' of AGN feedback that is likely to operate in massive galaxies at low redshifts.

2 EVOLUTION IN THE ABSENCE OF AGN FEEDBACK

We begin by considering whether natural evolution of the cold gas reservoir in star-forming early-types can produce the $(u - r)$ colour transition observed in S07, without the need for invoking feedback. Star formation depletes this gas reservoir which causes the galaxy to redden (assuming it is not replenished by accretion of fresh gas). To describe this secular evolution, we appeal to the Schmidt-Kennicutt law (e.g Schmidt 1959; Kennicutt 1998a; Boissier et al. 2003; Gao & Solomon 2004), which describes an apparently universal relationship between star formation rate (SFR) and cold gas mass across almost five decades of gas densities and SFRs in the galaxy population. Extensively established for disk galaxies and starbursts (see e.g. Kennicutt 1998a,b, and references therein), recent work indicates that the Schmidt-Kennicutt law also holds for early-type galaxies. In a study of CO emission in 43 representative early-type galaxies from the SAURON survey, Combes et al. (2007) and Crocker et al. (2010) have shown that early-types form a low-SFR extension to the empirical law in spirals. Given its universality and applicability to early-type galaxies, it is reasonable to model the colour evolution of the star-forming early-types, in the absence of feedback, using a Schmidt-Kennicutt law.

The Schmidt-Kennicutt law can be parametrised in terms of either the gas density or the gas mass. Since we only have measurements of the cold gas mass in early-type galaxies from S09, it is more relevant to cast the Schmidt-Kennicutt law in terms of this quantity. It is worth noting that star formation recipes in cosmological models of galaxy formation (e.g. semi-analytical models), where the galaxies are spatially unresolved, also commonly employ an Schmidt-Kennicutt law parametrised in terms of the gas mass (see e.g. Somerville & Primack 1999; Cole et al. 2000; Hatton et al. 2003; Kaviraj et al. 2005; Bower et al. 2006; De Lucia et al. 2006). These star formation recipes, tuned to reproduce the empirical constraints of Kennicutt (1998a), enable good reproduction of the properties of the galaxy population in the local Universe e.g. the observed luminosity functions in optical filters, the colours of the local galaxy population and the morphological mix of the Universe at present day. Following the typical parametrisations used in models (see e.g. Guiderdoni et al. 1998; Hatton et al. 2003), the Schmidt-Kennicutt law can be expressed as:

$$\psi = (\epsilon/\tau_{dyn}).M_g, \tag{1}$$

where ψ is the star formation rate, ϵ is the star formation efficiency, τ_{dyn} is the dynamical timescale of the system and M_g is the mass of the cold gas reservoir. The observed values of these parameters in the empirically-determined Schmidt-Kennicutt law for spiral disks (Kennicutt 1998a; Guiderdoni et al. 1998), indicate that $\epsilon \sim 0.02$ and $\tau_{dyn} \sim$ 0.1 Gyrs (given typical dynamical timescales of the gas disks). Before we can study the expected evolution of early-types via the Schmidt-Kennicutt law, we need to establish typical values of ϵ, τ_{dyn} and M_g that are relevant to the S07 early-type population.

We assume that the star formation efficiency (ϵ) is the fiducial 2% observed in the empirical Schmidt-Kennicutt law. Several studies over the last few decades have shown that giant molecular clouds convert around 1-2% of their mass over a dynamical timescale. This result appears independent of the choice of model for molecular-cloud lifetimes or evolution and holds irrespective of environment (see e.g. Tan et al. 2006; Krumholz & Tan 2007, and references therein). Coupled with the fact that the empirical Schmidt-Kennicutt law appears to hold for early-type galaxies (Combes et al. 2007; Crocker et al. 2010), it seems reasonable to assume the efficiency that underpins this star formation law. The median dynamical timescale of the S07 early-types, calculated using their (photometric) stellar masses and Petrosian radii, is $\sim$ 0.08 Gyrs. This value falls within the range of the measured dynamical timescales (0.05-0.2 Gyrs) of cold, molecular gas disks observed in *very* nearby early-type galaxies (Young 2002), which presumably drive the recent star formation. Note that these dynamical timescales correspond to galaxies in the local Universe - the corresponding timescales in the higher redshift Universe are likely to be smaller. The cold gas fractions in the star-forming early-types can be estimated using the measured cold gas and stellar masses in S09. The stacked data in S09 indicate that the cold gas fractions remaining in the star-forming early-types when they are observed are in the range 5-10%. Since the mass fractions in young stars that have already formed in these systems is also a few percent, the initial cold gas fractions are likely to be in the range 10-15%. This is consistent with (and slightly lower than) the gas fractions that may be inferred from Kannappan (2004), who measured the (atomic) gas to stellar mass ratios for SDSS galaxies using the Hyperleda HI catalogue. Their results for galaxies at $(u-r) \sim 1.5$ and masses between 10^{10} and 10^{11} $M_{\odot}$ suggest molecular gas fractions around 15-25% (after converting from atomic to molecular gas mass using the calibrations for early-type galaxies given by Fukugita et al. 1998). Note, however, that Kannappan (2004) did not split their galaxies by morphology and that their sample is certainly skewed towards gas-rich galaxies. Nevertheless, their results provide a useful sanity check of our assumptions for the initial cold gas fractions in our star-forming early-type galaxy sample.

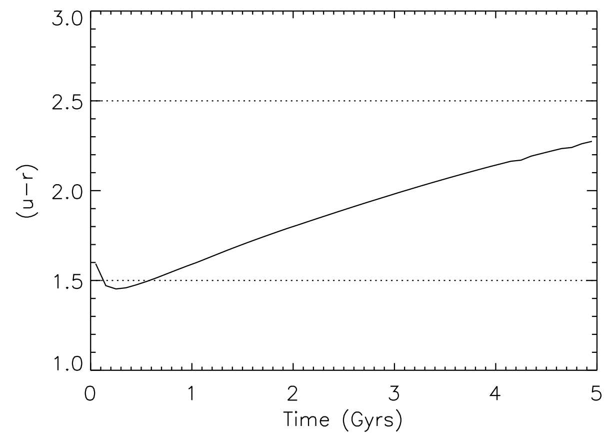

Figure 1. The expected evolution of a galaxy according to the Schmidt-Kennicutt law (Eqn. 1) where the star formation efficiency (ϵ) is 0.02, τ_{dyn} is 0.05 Gyrs and the initial cold gas fraction is 10%. The resultant evolution in the $(u-r)$ colour (in the absence of any AGN feedback) is too slow to reproduce the rapid transition from blue cloud to red sequence of early-type galaxies in S07. It is worth noting that, given its empirical nature, the Schmidt-Kennicutt law includes the impact of supernovae feedback on the star formation sites in the galaxy. Note also that the evolution shown here does not take into account any fresh injection of gas into the system through stellar mass loss or accretion from the halo. Both of these processes would further increase the migration time from blue cloud to red sequence.

We proceed by modelling the evolution of a typical star-forming early-type by considering a recent starburst, evolving according to Eqn. 1, superimposed on an old underlying stellar population. The underlying population is modelled using a simple stellar population (SSP) with solar metallicity and an age of 9 Gyrs. The motivation for an old, solar-metallicity SSP is the extensive literature on early-type galaxies which convincingly demonstrates that the bulk of the stars ($\geq 85-90\%$) in these galaxies form at high redshift, possibly over short timescales (Bower et al. 1992; Thomas et al. 2005, Kaviraj et al. 2008a,b) and that the stellar populations in present-day early-types are typically metal-rich (Trager et al. 2000a) with a mean value around solar metallicity. Note that our results are insensitive to small changes in the age or metallicity of this old SSP, because the old population does not contribute significantly to the u-band flux in a star-forming early-type galaxy.

In Figure 1 we show the expected $(u-r)$ colour evolution of a model early-type that evolves according to the Schmidt-Kennicutt law. We study the colour evolution between $(u-r) = 1.5$ (which represents the mean colour of the bluest 25% of the star-forming early-type population) and $(u-r) = 2.5$ (which represents the bottom of the red sequence defined by the quiescent early-type galaxies). Following the arguments above, we assume that ϵ is 0.02, τ_{dyn} is 0.05 Gyrs and the cold gas fraction is 10%. Note that, to be conservative in our approach, we have chosen the lower limit for the likely dynamical timescales and cold gas fractions in the S07 early-types, which corresponds to the fastest possible colour evolution. In principle, if the colour evolution due to natural evolution of the cold gas reservoir is fast enough to be consistent with the results of S07, then there would be no need for additional feedback on the system.

Figure 1 indicates that the reddening rate due to pure Schmidt-Kennicutt evolution [$d(u-r)/dt \sim 0.16$ Gyr^{-1}], is not sufficient to move the galaxy from the blue cloud ($u-r \sim 1.5$) to the bottom of the red sequence ($u-r \sim 2.5$) in ~ 1 Gyr, as suggested by S07. The reddening rate is a few factors too slow. It is worth noting that our model does not assume either stellar mass loss or accretion of gas from the halo, both of which would slow the depletion of the gas reservoir and the reddening rate even further. This suggests that, if the star-forming early-types were simply depleting their cold gas reservoirs through star formation alone, then they might be rather long-lived blue-cloud objects, similar to their spiral counterparts at similar colours. This is not unexpected if the early-types follow the same star formation laws as their late-type counterparts as has been suggested by the studies of Combes et al. (2007) and Crocker et al. (2010). Since the observed colour transition is much faster, it is then reasonable to suggest that an additional mechanism needs to be invoked to accelerate the depletion of available cold gas in the star-forming early-type galaxies. It is worth noting that modern galaxy formation models already incorporate the *result* of this effect, since massive galaxies in these models remain too blue in the absence of AGN feedback. The analysis above isolates this issue and demonstrates explicitly how the blue-to-red transit times are too long if the gas reservoir is depleted due to star formation alone.

The *coincidence* of AGN activity and the rapid observed evolution in the $(u-r)$ colour strongly suggests that the AGN may play a significant role in the migration of early-types from the blue cloud to the red sequence. In the following section we develop a simple model, in which feedback from the AGN accelerates the depletion of the cold gas reservoir, inducing a faster colour transition that is consistent with that observed in S07. The characteristics of the feedback episode are strongly constrained, *observationally*, by the observed migration times in S07, the estimated mass fractions of young stars in local early-type galaxies from the literature and residual cold gas fractions in S09. This allows us to put some useful constraints on (a) the strength of the coupling between the AGN and the cold gas reservoir and (b) the timescale over which that coupling holds.

3 A SIMPLE MODEL FOR AGN FEEDBACK

We develop a simple phenomenological model, in which some of the bolometric luminosity of an AGN couples to the cold disk gas reservoir and removes some of this gas mass, thus accelerating gas depletion and increasing the $(u-r)$ reddening rate. Given recent observational and theoretical evidence that outflows may play a dominant role in the AGN feedback process (see Section 1), the model assumes that cold gas is removed from the potential well, motivated by evidence for momentum-driven outflows contributing significantly to AGN feedback (see arguments above in the introduction). As noted in the introduction above, the trigger for the AGN in nearby early-types is likely to be the accretion of gas-rich satellites which induces a (weak) jet-driven outflow.

The coupling between AGN energy and the cold gas reservoir is determined by a 'feedback function' (f_t), which describes the fraction of the AGN's observed bolometric luminosity that is deposited into the cold gas reservoir and removes a portion of the gas mass. Thus we have, at time t:

$$f_t.L_B.\delta t = G.M.\delta M_g/R, \tag{2}$$

where L_B is the observed bolometric luminosity of the AGN, G is the gravitational constant, M is the mass of the galaxy, δM_g is the cold gas mass removed, R is the radius of the galaxy and δt is the size of the timestep being considered.

Note that the left-hand side (LHS) of Eqn. 1 could have been written simply in terms of the energy deposited into the cold gas reservoir i.e. without any reference to the luminosity of an AGN. In other words, the LHS could be expressed simply as a luminosity L_t, where $L_t \equiv f_t.L_B$. However, our chosen parametrisation allows to us to cast the feedback energy in terms of a reference luminosity which, in this case, is the observed luminosity of an AGN. The particular choice of reference luminosity L_B does not affect the total feedback energy entering the system of course, it simply allows us to express the feedback energy in terms of a useful observed quantity.

The form of f_t (see Figure 2 for a schematic representation) is assumed to be gaussian,

$$f_t = f_0.\exp\left[\frac{-(t-t_p)^2}{2\tau^2}\right], \tag{3}$$

with the following free parameters:

- f_0 is the peak fraction of the luminosity of an AGN that is deposited in the gas reservoir. It is a measure of how efficiently the AGN couples to the cold gas mass in the galaxy, since low values of f_0 will result in less gas being removed from the system and vice-versa.
- τ, the width of the gaussian, is a measure of the timescale over which the AGN interacts with the cold gas reservoir. This could, in principle, involve several AGN episodes over multiple duty cycles.
- t_p is the time at which the coupling is strongest. Since the conclusions in S07 indicate that the AGN activity peaks at roughly 0.5 Gyrs after the onset of star formation, we use a fiducial value of $t_p \sim 0.5$. Small changes to the value of t_p do not alter our conclusions.

With t_p held constant, our primary focus is on exploring the part of the (f_0,τ) parameter space that may reproduce the reddening rate observed in S07. As noted before, the models are constrained by three sets of observations - the recent star formation produced in the galaxy, the migration time between the blue cloud and the red sequence and the residual cold gas fractions in the galaxies when they arrive on the red sequence. Note that specifying the shape of the feedback function as a gaussian is somewhat arbitrary. However, the S07 results indicate that the AGN activity rises and falls within a Gyr, with a peak around 0.4 Gyrs. Given the simplicity of the model, a gaussian function appears a reasonable way to parametrise the feedback process.

We note that this is a simple model, decoupled from cosmological evolution, and geared towards studying star formation episodes in nearby early-type galaxies, triggered by discrete minor merger events. While the model is only designed to capture the broad characteristics of the feed-

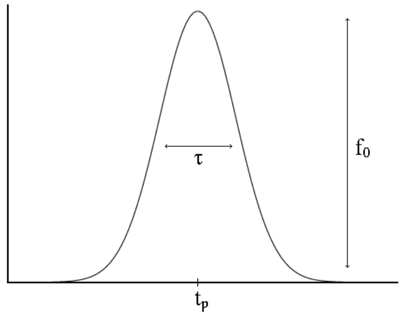

Figure 2. A schematic of the feedback function f_t. f_0 is the peak fraction of AGN luminosity that couples to the cold gas reservoir, τ is a measure of the timescale over which the AGN interacts with the cold gas reservoir and t_p is the time at which the coupling is strongest. The results of S07 indicate that t_p is ~ 0.5 Gyrs.

back process, its simplicity does not allow us to put constraints on details of the feedback e.g. the number of individual episodes of AGN activity or any modulation in the AGN output within an episode. Also recall that, while the model invokes the removal of cold gas - motivated by evidence for momentum-driven outflows contributing significantly to AGN feedback - it does not include the effects of radiative heating which may stop fresh gas cooling onto the disk. It is worth noting, however, that the early-type galaxies studied here reside in the field and are not central galaxies in cluster-sized haloes where the effects of cooling flows is expected to be most pronounced.

4 APPLICATION TO A TYPICAL STAR-FORMING EARLY-TYPE GALAXY IN THE BLUE CLOUD

We proceed by exploring feedback scenarios where a *typical* star-forming early-type galaxy in the blue cloud transits the gap between the blue cloud and the red sequence, in a manner consistent with the results of S07 and S09. Since the S07 results indicate that the mass fraction in young stars remains virtually constant through the reddening sequence, these early-type galaxies are the likely progenitors of the galaxies that are transiting via the green valley through to the red sequence.

To set up our model in terms of a typical star-forming early-type galaxy, we require typical values of the parameters that determine the feedback in Eqn 2. i.e. the mass (M) and radius (R) of the system. The median stellar mass of star-forming early-types in S07 is $\sim 5 \times 10^{10}$ M$_\odot$. We use the petrosian radius in the r-band, given by the SDSS `petrorad` parameter, as a measure of the galaxy radius. The median value of `petrorad` for the early-types in S07 is $\sim$ 8 kpc. We also require a value for the reference luminosity (L_B), for which we use the median AGN luminosity in the 'Seyfert' region of the S07 early-types. The bolometric luminosities of AGN can be calculated from the [OIII] λ5007 emission line luminosities - $L_B/L_{[OIII]} \sim 3500$ with a scatter of 0.38 dex (see Heckman et al. 2004, and references therein). The typical Seyfert region [OIII] luminosity in the S07 early-type sample is $\sim 10^{7.5}$ L$_\odot$. Thus, in what follows, we take the parameters M, R and L_B to be 5×10^{10}M$_\odot$, 8 kpc and 10^{11} L$_\odot$ respectively.

In a similar vein to Section 2, we construct scenarios where the object begins its evolutionary track around $(u-r) = 1.5$, which represents the mean colour of the bluest 25% of the star-forming early-type galaxy population. The transit times to the 'bottom' of the red sequence ($u-r \sim 2.5$) are in the range 0.5-2 Gyrs (the typical value is around a Gyr, see Figure 10 of S07). Thus our goal is to search for solutions where objects migrate between $u-r = 1.5$ and $u-r = 2.5$ within these transit times.

We begin by showing the general impact of feedback on the colour evolution of a model early-type galaxy. The left-hand panel of Figure 3 shows a scenario where (f_0,τ) = (10^{-3}, 0.07 Gyrs). The removal of cold gas from the reservoir is most efficient around t_p, the point at which the feedback reaches its peak. Recall that, following the results of S07, we assume $t_p = 0.5$ Gyrs in our model. Around t_p the gas fraction in the system experiences its sharpest decline, which induces a faster reddening in the $(u-r)$ colour than can be achieved through star formation evolution alone (indicated using the red ellipse). It is evident, however, that in this particular scenario, the feedback is not strong enough to produce the fast colour evolution observed in S07, since the galaxy still exhibits 'green valley' colours ($u-r \sim 2.2$) after 2 Gyrs of evolution.

We proceed by exploring the (f_0,τ) parameter space to search for scenarios where the $(u-r)$ reddening rate is consistent with the migration times in S07. We study scenarios where $10^{-4} < f_0 < 1$ and $0.01 < \tau < 1$ Gyrs. The right-hand panel of Figure 3 shows a scenario where (f_0,τ) = (0.005, 0.12 Gyrs), which reproduces the observed transit times reported by S07. The migration time in this model is ∼0.8 Gyrs and the mass fraction in young stars is ∼3%. The left-hand panel of Figure 4 presents a summary of the migration times for the scenarios discussed above, while the right-hand panel shows the mass fractions in young stars forming in each model. The dark grey regions of the plot are not allowed because the feedback is too weak - models in this region have migration times in excess of ∼ 2.5 Gyrs. Note that the scenarios shown coloured in Figure 4 bracket the S07 migration times (0.5-2 Gyrs). The light grey regions on the right are not allowed because the feedback is too strong. In these scenarios, the cold gas mass is depleted so quickly that the galaxy never gets a chance to reach $u-r \sim 1.5$ in the first place.

We find that a part of the parameter space does satisfy the migration times (shown colour-coded) observed in S07. These scenarios typically have feedback timescales $\lesssim 0.2$ Gyrs (left-hand panel) and produce mass fractions in young stars ranging from less than a percent to ∼ 5 percent (right-hand panel). Not unexpectedly, the τ and f_0 values in these acceptable scenarios are to some extent degenerate in the expected way - longer AGN timescales require lower coupling efficiencies and vice versa. We find that, for these models, the residual cold gas fractions are $\lesssim 0.6$%, with the gas reservoirs already depleted by the time the galaxy arrives in the green valley, in good agreement with the results of S09. It is interesting to note that the coupling is relatively weak while the galaxy is in the blue cloud, which may be consistent with an apparent lack of high-luminosity AGN in blue early-types (Schawinski et al. al 2009b).

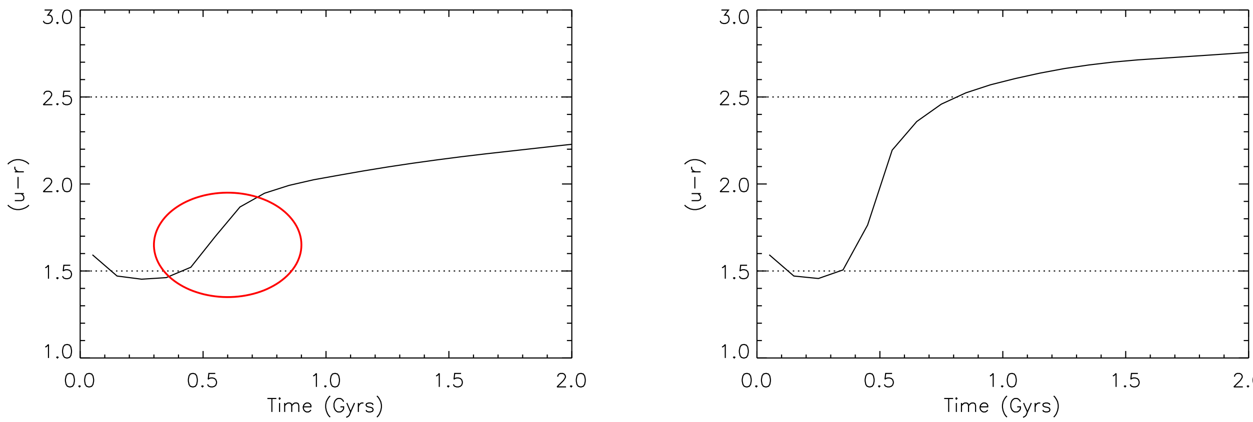

Figure 3. Two examples of feedback scenarios. The removal of gas from the reservoir is most efficient around $t_p = 0.5$ Gyrs, the point at which the AGN feedback reaches its peak (see Section 3). In the left-hand panel, we show a weak feedback scenario with parameters $(f_0,\tau) = (10^{-3}$, 0.07 Gyrs). The reddening induced in this scenario (highlighted by the red ellipse) is not fast enough to achieve the migration times in the S07 study because the galaxy is still in the 'green valley' after $\sim$2 Gyrs. In contrast, the right-hand panel shows a scenario which reproduces the fast migration times observed in S07, with parameters $(f_0,\tau) = (0.005$, 0.13 Gyrs). The galaxy transits the gap between the blue cloud and the red sequence within around a Gyr. Note, when comparing to Figure 1, that the time axes are shown only to 2 Gyrs in this figure.

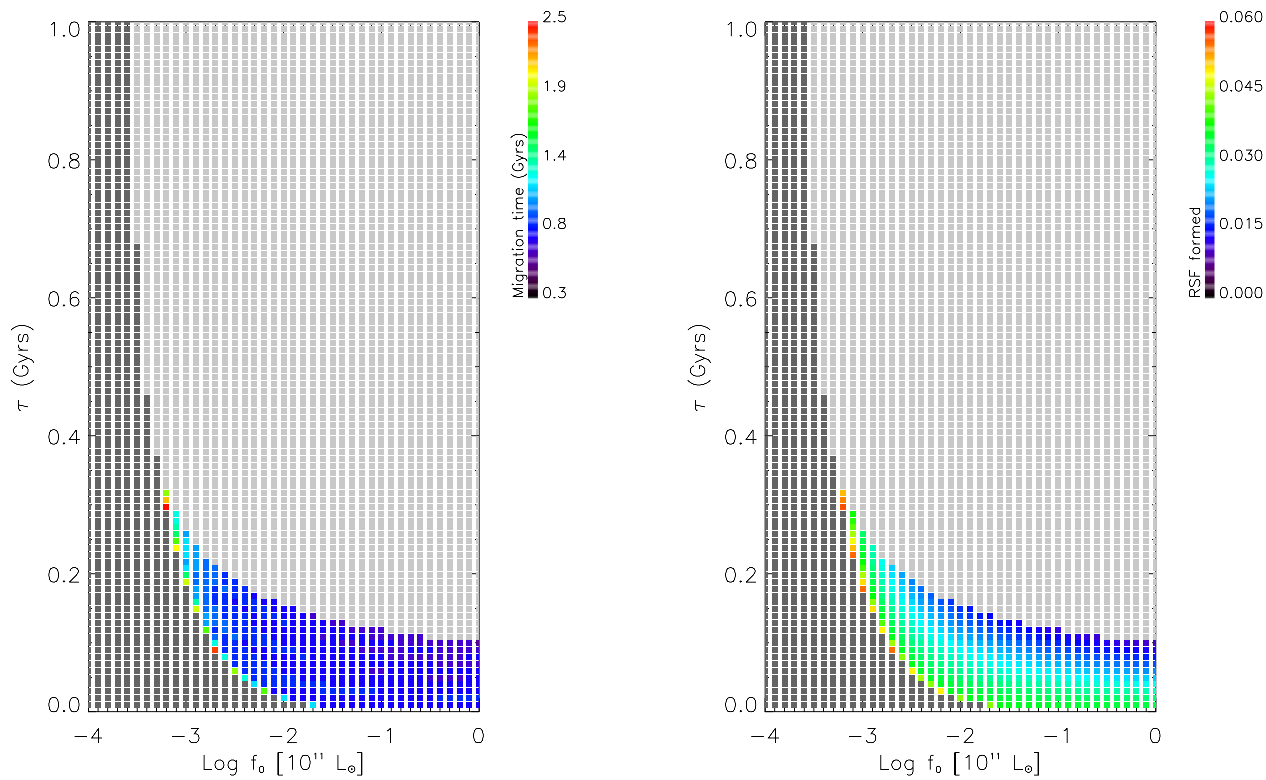

Figure 4. LEFT: The migration times from a set of feedback scenarios where $10^{-4} < f_0 < 1$ and $0.01 < \tau < 1$ Gyrs. The dark grey regions of the plot are not allowed because the feedback is too weak - models in this region have migration times in excess of ~ 2.5 Gyrs. The light grey regions on the right are not allowed because the feedback is too strong. Note that the scenarios shown coloured in this plot bracket the S07 migration times (0.5-2 Gyrs). RIGHT: The mass fractions in young stars for the scenarios shown on the left.

Our results suggest that, to achieve the migration times observed in S07, the original reservoir of cold gas in the star-forming early-types must be almost completely evacuated by the time the galaxy approaches the red sequence. Furthermore, since the mass fractions in young stars are less than $\sim$ 5 percent, more than half of the available fuel for star formation is likely to be lost to the intergalactic medium. Note that, since the measured young-star fractions in the blue S07 early-types are typically a few percent, scenarios which produce very small mass fractions (e.g. less than a percent) are unlikely. If we restrict ourselves further to the feedback timescales that are consistent with expected AGN duty cycles (a few hundred Myrs, e.g. Haehnelt et al. 1998; Martini & Weinberg 2001; Mathur et al. 2001; Shabala et al. 2008), then only a few tenths of a percent (10^{-3} to 10^{-2}) of the luminosity of a typical Seyfert AGN must couple to the cold gas reservoir to produce the observed migration times. Such scenarios produce mass fractions in young stars around 2-4% and leave remnants with cold gas fractions $\lesssim 0.6\%$, in good agreement with the data.

Finally, it is worth comparing the range of f_0 values derived in this study with similar estimates obtained using other methods. Ciotti et al. (2010) find that (radiation-driven) outflows only require coupling efficiencies of 10^{-3} to 10^{-2} between the AGN luminosity and the ambient cold gas to completely remove the gaseous component of the galaxy. Radio source modelling of the interaction between jets and their environments (e.g. De Young 1993; Sutherland & Bicknell 2007) suggest that values of 10^{-3} to 10^{-1} are possible. Observationally, studies of X-ray cavities and associated radio cocoons have revealed coupling efficiencies between 10^{-4} and 10^{-2} (Bîrzan et al. 2004). The coupling strengths derived here (a few tenths of a percent) therefore appear reasonably consistent with the aforementioned studies, which have derived coupling efficiencies using independent methods.

5 SUMMARY

A growing body of recent observational evidence now indicates that star formation at late epochs ($z < 1$) adds a significant minority of the stellar mass ($10 - 15\%$) in massive early-type galaxies (e.g. Kaviraj et al. 2008). While energetic arguments have made a compelling theoretical case for AGN feedback to regulate star formation in galaxy formation models, observational constraints on this putative process in the nearby early-type galaxy population has remained limited but are desirable.

In this paper, we have presented a strong plausibility argument for AGN feedback to play a significant role in the evolution of star-forming early-types at late epochs. Previous work in S07 has shown that star-forming early-types in the blue cloud show evidence for rapid migration to the red sequence, typically within a Gyr, passing through several phases of AGN activity as they move from the blue cloud ($u - r \sim 1.5$) to the red sequence. A standard 'BPT' analysis, using optical emission line ratios, indicates that early-types classified as 'star-forming' are the bluest, with those classified as 'composites', 'Seyferts', 'LINER' and 'quiescent' becoming progressively redder in that order. This is accompanied by a precipitous decrease in the cold gas mass in the system of an order of magnitude between the star-forming and Seyfert phases (S09).

Using recent results which indicate that star formation in early-types can be described by the empirical Schmidt-Kennicutt law, we have studied whether natural depletion of the cold gas reservoir in star-forming early-type galaxies, purely through Schmidt-Kennicutt-driven star formation, can produce the rapid colour migration observed in S07. We have shown that this colour migration is a few factors too slow, compared to what is observed by S07, essentially because the gas depletion rate is not adequately fast. It is therefore reasonable to suggest that, to achieve the observed reddening rate, an additional mechanism is required to accelerate the depletion of cold gas and induce a faster transition from the blue cloud to the red sequence. The coincidence of AGN activity and the rapid observed colour transition strongly suggests that the AGN may play a significant role in driving this gas depletion and the transit of galaxies from the blue cloud to the red sequence.

To explore the broad characteristics of this AGN-driven feedback we have developed a simple phenomenological model in which a fraction of the bolometric luminosity of the AGN couples to the cold gas reservoir and removes some of the gas mass, while the remaining gas continues to produce stars according to the Schmidt-Kennicutt law. The impact of this feedback is to accelerate the rate of gas depletion, which induces a faster colour transition that is consistent with the results of S07. Our results suggest that a few tenths of a percent of the luminosity of a Seyfert AGN ($\sim 10^{11}$ $L_{\odot}$) must couple to the cold gas reservoir of a typical star-forming early-type galaxy over a duty cycle (a few hundred Myrs) to induce a colour transition that is consistent with the findings of S07 and S09. Such scenarios lead to mass fractions in young stars of a few percent, with residual cold gas fractions of less than $\sim 0.6\%$, both consistent with the measurements of mass fractions of young stars in blue early-types and residual cold gas masses in Seyfert early-types. As we discuss in Section 4 above, the coupling efficiencies derived here are consistent with independently derived values in the literature.

We conclude by connecting the results in this paper to recent work on the evolution of early-type galaxies in the local Universe. As noted in the introduction, both theoretical and observational arguments indicate that the recent star formation in early-types is likely to be influenced by minor merging at late epochs. This is supported by evidence for kinematical decoupling between the (ionised) gas and stars and the fact that the gas mass shows no correlation with the stellar mass of the galaxy, irrespective of the local environment, both indicating that the gas is, at least in part, external in origin. The cold gas injected by gas-rich infalling satellites is likely to trigger low-level star formation which moves the spheroid temporarily to the blue cloud. This is followed by the fuelling of the central black hole and AGN activity, which reaches a peak around 0.5 Gyrs after the onset of star formation. In the time delay between the onset of star formation and the peak of the AGN activity, the induced star formation adds a few percent (or less) to the stellar mass of the original spheroid. The rise of the AGN then acts to rapidly quench the star formation and restores the spheroid to the red sequence over a short timescale (∼ 1 Gyr).

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