SUBMITTED TO APJL, JANUARY 26, 2006
Preprint typeset using LaTeX style emulateapj v. 6/22/04

OBSERVATIONAL EVIDENCE FOR THE CO-EVOLUTION OF GALAXY MERGERS, QUASARS, AND THE BLUE/RED GALAXY TRANSITION

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Submitted to ApJL, January 26, 2006

ABSTRACT

Observations indicate the mass above which ellipticals dominate the galaxy population increases with redshift over the range $0 < z < 2$, implying that galaxies transition from the blue to red sequence in a manner consistent with "cosmic downsizing." Theories predict that mergers between gas-rich blue galaxies produce ellipticals, with an associated phase of bright quasar activity which expels and heats gas, terminating star formation, so that the remnant rapidly becomes red. If this is true, then the transition mass at a given redshift, where the red sequence is being built, should also correspond to the characteristic mass of both merging gas-rich galaxies and quasar hosts at that redshift. We compare observations of these quantities from $0 < z < 3$, as well as theoretical models of mergers and associated quasar activity, and show that they indeed appear to be the same mass and evolve in the same manner over this range. We also provide new tests of this association, such as the AGN fraction peaking near the transition mass and the quasar host mass as a function of luminosity. Our results support the view that mergers and subsequent quasar activity drive the transition of galaxies from the blue to the red sequence.

Subject headings: quasars: general — galaxies: active — galaxies: evolution — cosmology: theory

1. INTRODUCTION

Observations motivate the notion of "cosmic downsizing" (e.g., Cowie et al. 1996; Madau et al. 1996; Brinchmann et al. 1998; van Dokkum et al. 2000; Treu et al. 2002), with the global star formation rate declining rapidly below $z \sim 2$, and the sites of star and galaxy formation shifting to smaller masses at lower redshift. Moreover, galaxy surveys such as SDSS, COMBO-17, and DEEP2 demonstrate that the color distribution of galaxies is bimodal (e.g., Strateva et al. 2001; Balogh et al. 2004), and that this bimodality extends at least to $z \sim 1$ (e.g., Bell et al. 2004; Faber et al. 2005). High mass, red elliptical galaxies seem to be largely in place by $z \sim 2$, with more recent formation times for smaller spheroids (e.g., Treu et al. 2005). These trends appear to run counter to the most basic assumptions of hierarchical structure formation, and thus understanding the nature and physical drivers of downsizing and the difference between the red and blue populations are crucial to modeling galaxy formation.

Even more recently, measurements of galaxy stellar mass functions (MFs) at redshifts $0 < z < 2$, separated by color or galaxy morphology (Bundy et al. 2005a,b; Franceschini et al. 2006; Pannella et al. 2006) have shown that the "buildup" at low masses occurs primarily at the low-mass end of the red galaxy MF (which dominates the total MF at high mass), while the blue, disk-dominated, star-forming galaxy mass function (dominant at low mass) remains relatively constant. These studies have found that the "transition mass," above which the red galaxy population dominates the galaxy MF, increases with redshift, tracing this downsizing trend. As low-mass, red galaxies build up, the mass of the largest star-forming galaxies, although less well-constrained, decreases correspondingly, indicating that star formation is "quenched" in these systems and that they move to the red sequence (Bundy et al. 2005b). Meanwhile, the discovery of tight correlations between the masses of central supermassive black holes (BHs) in galaxies and the bulge or spheroid stellar mass (Magorrian et al. 1998) or velocity dispersion (Gebhardt et al. 2000; Ferrarese & Merritt 2000) implies that the formation of the two must be linked. Moreover, the evolution of the quasar luminosity function (QLF) appears to follow a qualitatively similar "downsizing" trend, with the density of lower-luminosity AGN peaking at low redshift (e.g., Hasinger, Miyaji, & Schmidt 2005, and references therein).

Taken together, these observations motivate a picture for galaxy and BH co-evolution, in the context of the merger hypothesis (Toomre 1977). Mergers between blue, star-forming galaxies channel large amounts of gas to galaxy centers, fueling powerful starbursts and buried BH growth (e.g., Sanders et al. 1988; Barnes & Hernquist 1992) until the BH grows large enough that feedback from accretion rapidly unbinds the surrounding gas, expelling and heating it (Silk & Rees 1998). This terminates both star formation and BH growth, leaving a red elliptical satisfying observed correlations between BH and spheroid mass. Mergers proceed efficiently at high redshift, building up the high-mass elliptical MF, but once formed these galaxies are "dead", and mergers involving gas-rich galaxies transition to lower masses.

Hydrodynamical simulations, incorporating star formation, supernova feedback, and BH growth and feedback (Springel et al. 2005b) make it possible to study these processes self-consistently. Mergers with BH feedback yield remnants resembling observed ellipticals in their correlations with BH properties (Di Matteo et al. 2005), scaling relations (Robertson et al. 2005b), colors (Springel et al. 2005a), and morphological properties (Cox et al. 2005). The quasar activity excited through such mergers can account for the QLF and a wide range of quasar properties at a number of frequencies (Hopkins et al. 2005a,e), and with such a detailed model to "map" between merger, quasar, and remnant galaxy populations it is possible to show that the buildup and statistics of the quasar and red galaxy populations are consistent and can be used to predict one another (Hopkins et al. 2005f).

In this picture, the "transition mass" (M_{tr}) may represent the "smoking gun" of mergers causing the flow of galaxies

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from the blue to red sequence. It is a strong prediction of these theories, and specifically the modeling of Hopkins et al. (2005a-h) that the same mergers are responsible for the bulk of the bright quasar population and the buildup of the red sequence at each redshift. Therefore, to the extent that M_{tr} traces the mass at which the red sequence is being "built" at some z, it should also trace the characteristic mass of star-forming galaxies merging at that time, and the characteristic mass of galaxies hosting quasars which are initially triggered by those mergers. Here, we consider the observed M_{tr} over the range $0 < z < 2$, and compare it to the characteristic masses of quasar hosts and merging galaxies over the same range in redshift and demonstrate that they appear to be evolving in a manner consistent with our merger-driven unification picture of quasars, interacting galaxies, and the red galaxy population.

We adopt a $\Omega_{\rm M} = 0.3$, $\Omega_{\Lambda} = 0.7$, $H_0 = 70\,{\rm km\,s^{-1}\,Mpc^{-1}}$ cosmology.

2. COMPARING THE TRANSITION MASS TO QUASARS AND MERGERS

In what follows, we take the transition mass M_{tr} to be the galaxy stellar mass at which the number densities of blue and red (color-selected) galaxies are equal. Ideally we would consider the "quenching mass" M_Q (Bundy et al. 2005b) at which the blue (star-forming) MF cuts off, which has a more immediate physical interpretation, but is harder to quantify (and appears to be simply systematically larger by a factor $\sim 1.5-2$). We compile M_{tr} from several morphologically and color-separated MFs (Bell et al. 2003; Pozzetti et al. 2003; Fontana et al. 2004; Bundy et al. 2005a,b; Pannella et al. 2006). Where possible, we uniformly use K-band selected samples, but to contrast we consider the B-band luminosity functions in the range $z = 0-1$ from COMBO-17 and DEEP2 (Bell et al. 2004; Willmer et al. 2005; Faber et al. 2005), and convert these to MF estimates using the mass-to-light ratios of van der Wel et al. (2005). The difference in the derived M_{tr} is small, and within observational uncertainty, but in more detailed comparison the value of M_{tr} does depend on the sample division and completeness corrections. The results are plotted in Figure 1 (black points, as labeled). Horizontal errors show the width of the observed redshift intervals, and vertical errors the uncertainty in M_{tr} from the observed 1σ MF uncertainties. Even with the large uncertainties at each point, the observations agree and a trend of increasing M_{tr} with z is apparent over the observed range $z \sim 0-2$.

The observed QLF is well characterized by luminosity evolution, with an evolving break luminosity L_* at (approximately) constant number density ϕ_*. This, then, naturally defines a characteristic mass. If quasars at or above the break are accreting near their Eddington rates, and obey the correlation between the BH and (total) host galaxy spheroid stellar mass ($M_{\rm BH} \approx 0.001\,M_{\rm host}$; Magorrian et al. 1998; Marconi & Hunt 2003), this implies $M_{\rm host}/M_{\odot} \sim 0.03\,L_{\rm bol}/L_{\odot}$. Indeed, this relation is seen to apply to active quasars at least up to $z \sim 2$ (e.g., Peng et al. 2006), and many observations constrain their Eddington ratios to approximately unity (e.g., Kollmeier et al. 2005). There is some uncertainty and observed scatter in the host galaxy-BH mass correlation and bright quasar Eddington ratios, but it is constrained to a factor ~ 2, comparable to the uncertainty in the observed M_{tr}.

We determine the break as a function of redshift by fitting the QLF as a function of redshift to the combined binned observations of Ueda et al. (2003); Hunt et al. (2004); Richards et al. (2005); Barger et al. (2005); La Franca et al. (2005); Hao et al. (2005); Hasinger, Miyaji, & Schmidt (2005); Richards et al. (2006), de-convolving over the observed column density distributions from Ueda et al. (2003); La Franca et al. (2005). We determine bolometric corrections modeling the intrinsic quasar continuum SED following Marconi et al. (2004), based on optical through hard X-ray observations (e.g., Elvis et al. 1994; George et al. 1998; Vanden Berk et al. 2001; Perola et al. 2002; Telfer et al. 2002; Ueda et al. 2003; Vignali et al. 2003), with a reflection component generated by the PEXRAV model (Magdziarz & Zdziarski 1995). For details, see Hopkins et al. (2005e).

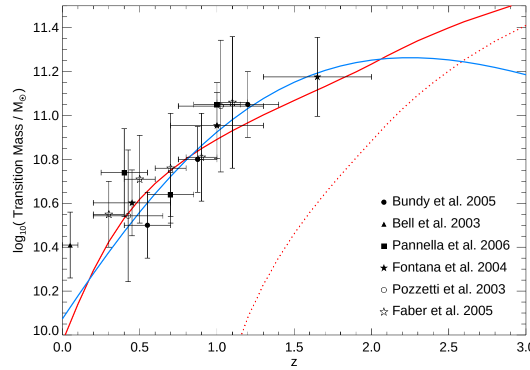

FIG. 1.— Observed transition mass (mass at which number densities of blue and red galaxies are equal) as a function of redshift (points, as labeled). The host galaxy mass corresponding to quasars at the observed break in the QLF (from e.g., Ueda et al. 2003; Richards et al. 2005; Hasinger, Miyaji, & Schmidt 2005), is shown (blue), as is the calculated transition mass from a full deconvolution of the observed QLF from $z = 0-6$ using simulated galaxy mergers (Hopkins et al. 2005a-f) to determine the quasar lifetime and correlations with host galaxy mass (red solid). The same deconvolution, but instead adopting a "light bulb" or exponential light curve quasar model (equivalently, ignoring quasar feedback) is shown (red dotted).

The host galaxy mass corresponding to the observed QLF break L_* is plotted in Figure 1 as a function of redshift (blue line). The uncertainties from the observational fitting are not shown, because they are smaller than the typical uncertainties in the host galaxy mass relation. Ultimately, adopting a much simpler comparison with e.g. the fitted $L_*(z)$ (after bolometric correction) from any of the observed QLFs above which span the relevant redshift range yields an essentially identical result, especially within the $\sim 0.2\,$dex uncertainty in M_{tr}. In any case, the characteristic host mass of quasars at the observed QLF break L_* agrees well with M_{tr} over the observed redshift range.

A more detailed comparison requires adopting some model for quasar light curves and triggering. Hopkins et al. (2005e,g) use a large set of hydrodynamical simulations (Robertson et al. 2005a,b) of galaxy mergers varying the relevant physics to quantify the quasar lifetime as a function of both the observed and peak quasar luminosity. The peak luminosity $L_{\rm p} \approx L_{\rm Edd}(M_{\rm BH})$ is approximately the Eddington luminosity of the final (post-merger) BH mass, which obeys the observed correlations with host galaxy properties. The lifetime $t_Q(L\,|\,L_{\rm peak})$ represents a PDF for observing a given BH in a given host at some luminosity. With this quantity, it is straightforward to de-convolve the observed QLF to determine the rate at which quasars of given $M_{\rm BH}$ are born through mergers (see Hopkins et al. 2005c). In this manner, we find that the quasar birthrate rate is *peaked* at a characteristic $L_{\rm p} \sim L_*(z)$ corresponding to (and indeed determining) the observed QLF break at all z, with a characteristic host stellar mass given by the relation used above ($M_{\rm BH,\,Edd}(L_{\rm p}) \sim 0.001\,M_{\rm host}$).

If each major gas-rich galaxy merger triggers a bright quasar which subsequently decays, and each such merger leaves a remnant, reddening spheroid, then the simulations allow us to map the observed QLF into the buildup of the red sequence mass or luminosity functions. Adopting this model (see Hopkins et al. (2005e,f) for details), then, the observed QLF implies a buildup of the red galaxy MF as a function of redshift. From work by several groups (e.g., Pozzetti et al. 2003; Fontana et al. 2004; Dahlen et al. 2005; Bundy et al. 2005a; Franceschini et al. 2006), the spiral mass function is reasonably well-measured over the range of interest, and evolves weakly, with typical uncertainties less than or comparable to the measured M_{tr}. We compare the two to predict M_{tr} at $0 < z < 2$, and show this prediction in Figure 1 (red solid line). Indeed, both the pure observational estimate and more detailed calculation match the observed $M_{tr}(z)$ well.

If, however, we model the quasar lifetime in an idealized manner, assuming e.g. a simple step-function "light bulb" model, or an exponential decay for the quasar light curve, it implies a trivial relation between the rate of triggering and the observed QLF, namely that the two have identical shape, steeply rising at low luminosities. This yields a qualitatively different M_{tr}, shown in Figure 1 (red dotted line). In such a picture, the break in the QLF no longer has physical significance, implying that the relation between M_{tr} and $L_*(z)$ observed is simply a coincidence, and the predicted M_{tr} is not at all consistent with that observed. If we ignore BH feedback, which drives the quasar to lower luminosities after the merger, the light curve resembles a "light bulb" model, and a similar disagreement results.

In our picture, M_{tr} and the characteristic quasar host mass at L_* are the same because both are driven by mergers between blue galaxies building up the red sequence, and terminating in quasar activity. We therefore expect that the characteristic mass of merging galaxies observed at each redshift should also trace this same relation. To test this, we determine the M_*, corresponding to the characteristic stellar mass of merging galaxies at a given redshift (i.e. the turnover in the Schechter or double-power law merger MF) from observed samples. The pair-selected sample of Xu et al. (2004) (2MASS) and morphologically identified samples of Conselice et al. (2003, 2005) (HDF-N and HDF-S) and Bundy et al. (2005b) (DEEP2) in K-band yield direct mass estimates. We convert optical and near-UV observations to stellar mass distributions following Hopkins et al. (2005e); Jonsson et al. (2005), who determine the probability of observing a given luminosity in a merger as a function of stellar mass using the simulations of Robertson et al. (2005b). For all stars in the simulation, this combines the self-consistent star formation and metal enrichment history with stellar population synthesis models and the radiative transfer along all sightlines from the multi-phase ISM gas to give a PDF in observed luminosity vs. stellar mass at all merger stages. The results are shown for the observations of Wolf et al. (2005) (GEMS and GOODS), Brinchmann et al. (1998) (CFRS and LDSS) and Toledo et al. (1999). Note that a mass or luminosity+number density is sufficient to determine M_* if the functional form is similar at different z, observed at $z = 0$ and $z = 0.7$ (Xu et al. 2004; Wolf et al. 2005), and changing this

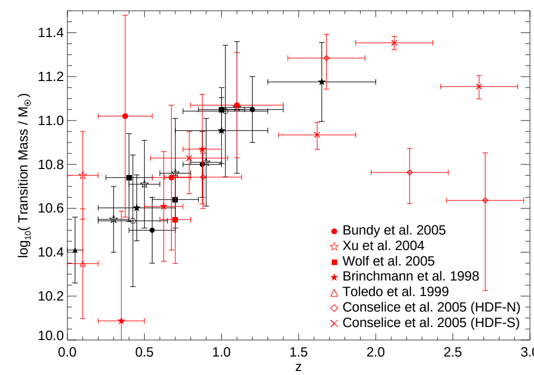

FIG. 2.— Observed transition mass as in Figure 1 (black points), compared to observed characteristic mass of merging galaxies (M_* or peak of the merger mass function) at various redshifts (red points, as labeled).

only changes the observations within the existing uncertainties. A detailed comparison with these results will be performed in due course, but the theoretical uncertainties are small (see, e.g. Hopkins et al. 2005e; Jonsson et al. 2005), and mergers tend to have flat optical stellar light curves, simplifying the comparison. Ultimately, the morphologically and pair-selected, as well as optical, UV, and K-band estimates all agree well up to the $z \gtrsim 2$ estimates, which have been determined from small samples and are significantly affected by cosmic variance (Conselice et al. 2005). The observed M_* is plotted in Figure 2 (red points, as labeled), with the observed M_{tr} (black points) from Figure 1. Again, the two appear to trace the same mass over the observed $0 < z < 2$.

While the observations are suggestive, systematic uncertainties remain large. Le Fèvre et al. (2000) find that pair and morphological selection criteria yield similar results, but Lin et al. (2004) find significant disagreement. Fortunately, our comparison relies only on the characteristic merger mass (or luminosity) which should not change dramatically with selection method even though the time spent in a given phase (and thus ϕ_* or merger fraction) may. Indeed, the data of Lin et al. (2004) and Conselice et al. (2003) do suggest a similar characteristic M_B, despite their finding different merger fractions. Wolf et al. (2005) also find that the observed number of faint mergers depends strongly on selection effects, which can be somewhat controlled if only the merger M_* is of interest but must be accounted for in any comparison of fitted MFs. Another critical distinction is the separation of interacting galaxies from very physically distinct late-type irregulars, which are typically combined in a "Pec/Irr" category for statistics (yielding a late-type dominated Pec/Irr MF).

3. TESTS OF THIS ASSOCIATION

From our modeling of quasar lifetimes, the deconvolution of the QLF yields the contribution to the observed QLF from mergers with different peak quasar luminosities or host stellar masses. In Figure 3 (left) we show the observed QLF at $z = 0.2$ (Ueda et al. 2003; Hao et al. 2005) (converted to B-band with the SED modeling described above; dotted line). Deconvolving with our simulated light curves, we show the contribution to the QLF from hosts/merger remnants with different masses relative to the observed transition mass (from Bell et al. 2003, at this z), as labeled (binned by ± 0.5 dex in $M_{\rm host}$). As shown above, most of the QLF, especially at the observed break, corresponds to objects with $M_{\rm host} \sim M_{tr}$ at

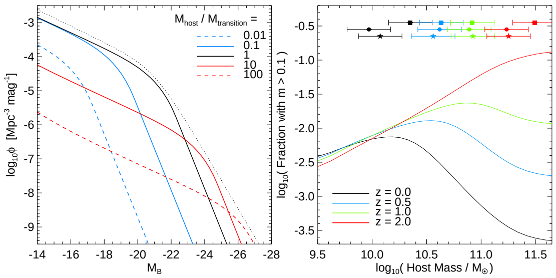

FIG. 3.— Left: Predicted contribution to the total (unobscured) B-band QLF (dotted, from Hao et al. (2005) and Ueda et al. (2003)) from host galaxies in different mass intervals relative to the observed transition mass as labeled, from the models of Hopkins et al. (2005a-h) (shown at $z = 0.2$, but qualitatively similar at all redshifts of interest). Right: Predicted fraction of galaxies hosting an AGN with an accretion rate (relative to Eddington) $\dot{m} > 0.1$, as a function of mass, at different redshifts as labeled. Points of the corresponding color show the observed transition mass at each redshift.

that z. At the faintest and brightest M_B there are contributions from smaller and larger hosts, respectively, but it is clear from the Figure that a direct measurement of the host masses of characteristic quasars at z should find their hosts dominated by objects with $M_{\rm host} \sim M_{tr}$. Although we show results at $z = 0.2$, the result (relative to the co-evolving M_{tr} and QLF break L_*) at each z of interest is similar. In our modeling, we expect many of these bright objects to appear as relatively young ellipticals, formed recently in mergers with decaying quasar activity.

From the same deconvolution of the observed QLF, one might also expect that objects with masses $\sim M_{tr}$ preferentially host AGN. We use this deconvolution to predict the fraction of galaxies hosting an AGN with an accretion rate (relative to Eddington) $\dot{m} > 0.1$ as a function of galaxy stellar mass, at redshifts $z = 0,\ 0.5,\ 1.0,\ 2.0$. This is shown in Figure 3 (solid lines, as labeled). For comparison, points of the corresponding color show the observed transition mass at each redshift (with horizontal errors showing observational uncertainty), in the style of Figure 1. At each z, the predicted AGN fraction is peaked at $M_{tr}(z)$. Note, however, that this is quantified in terms of $\dot{m}$, so the actual AGN luminosity will be $\dot{m}\,L_{\rm Edd}(M_{\rm BH})$.

4. DISCUSSION

We find that the observed "transition mass" M_{tr}, above which red, elliptical galaxies dominate the galaxy MF, corresponds directly to the observed characteristic masses of $\sim L_*$ quasars and $\sim M_*$ galaxy mergers over the range $0 < z \lesssim 2$. If we assume that the red sequence is built up through mergers which terminate in observed quasar activity, we can use the quasar light curves from the simulations of Hopkins et al. (2005e) to predict, from the observed QLF, the detailed evolution of M_{tr} with redshift, which yields an essentially identical prediction. If, however, we consider a simplified "light bulb" or exponential light curve model for quasars, this theoretical prediction is strongly discrepant with the observations.

That mergers and quasars trace M_{tr} and its evolution supports the hypothesis that mergers drive the transition from blue disks to red elliptical galaxies, terminating in decaying, feedback-driven bright quasar phases. The transition mass and break in the QLF reflect the characteristic mass of gas-rich objects merging at a given redshift, building up the red sequence at progressively lower masses at lower z as gas supplies are exhausted at high masses. Improved measurements of $M_{tr}(z)$ and $M_Q(z)$ to higher redshift and the characteristic masses of mergers can provide strong constraints on this process. The distribution of merger masses (as opposed to a simple mass density or fraction), can also enable a purely observational test of this picture through the integration of the merger MF and comparison with the remnant, red galaxy MF. We also predict that the observed QLF should be dominated (especially near the break), by hosts with $M_{\rm host} \sim M_{tr}$, and that the AGN fraction (defined by high Eddington ratio) should peak near M_{tr}, at each redshift, which present simple tests of this association.

This work was supported in part by NSF grants ACI 96-19019, AST 00-71019, AST 02-06299, and AST 03-07690, and NASA ATP grants NAG5-12140, NAG5-13292, and NAG5-13381.

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