Dynamical delays between starburst and AGN activity in galaxy nuclei

Philip F. Hopkins

Department of Astronomy and Theoretical Astrophysics Center, University of California Berkeley, Berkeley, CA 94720, USA

Accepted 2011 October 19. Received 2011 October 18; in original form 2011 January 17

ABSTRACT

Observations of active galactic nuclei (AGN) have suggested a possible delay between the peak of star formation (on some scale) and AGN activity. Inefficient fuelling (and/or feedback) from fast stellar winds has been invoked to explain this, but we argue this is unlikely in bright systems accreting primarily cold dense gas. We show that such a delay can arise even in bright quasars for purely dynamical reasons. If some large-scale process produces rapid inflow, smaller scales will quickly become gas dominated. As the gas density peaks, so does the star formation rate (SFR). However, gravitational torques which govern further inflow are relatively inefficient in gas-dominated systems; as more gas is turned into stars, the stars provide an efficient angular momentum sink allowing more rapid inflow. Moreover, the gas provided to the central regions in mergers or strong disc instabilities will typically be \( \sim \) 100 times larger than that needed to fuel the black hole (BH); the system is effectively in the ‘infinite gas supply’ limit. BH growth can therefore continue for some time while the gas supply exhausts, until it has significantly depleted to the point where the BH is finally ‘starved’. Both of these effects act together with comparable magnitude, and mean that the peak of BH growth can lag the peak in the SFR measured at a given scale by a time-scale corresponding to the gas exhaustion time on that scale (\( \sim \) 10–100 local dynamical times). This predicts that the inferred delay will vary in a specific manner with the radius over which the SFR is measured. We discuss possible implications for the role of AGN feedback in suppressing star formation activity.

Key words: galaxies: active – galaxies: evolution – galaxies: formation – quasars: general – cosmology: theory.

1 INTRODUCTION

The idea of a connection between active galactic nuclei (AGN) and starburst activity in galaxies has a long history, going back to speculation that dense nuclear gas concentrations in ultra-luminous infrared galaxies fuel supermassive black holes (BHs) that eventually appear as luminous quasars, expelling the nuclear gas and dust (Joseph 1999; Sanders 1999). The discovery of tight correlations between the mass of nuclear BHs and their host bulge properties (Magorrian et al. 1998; Ferrarese & Merritt 2000; Gebhardt et al. 2000; Aller & Richstone 2007; Hopkins et al. 2007; Feoli & Mancini 2009) has suggested that BH and galaxy formation are coeval, and the cosmic history of BH growth has roughly similar shape to the cosmic star formation history (see e.g. Merloni, Rudnick & Di Matteo 2004). Observations have found AGN to preferentially live in hosts with enhanced star formation activity relative to control galaxy samples (Brotherton et al. 1999; Canalizo & Stockton 2001; Kauffmann et al. 2003; Jahnke, Kuhlen & Wisotzki 2004; Sánchez et al. 2004; Vanden Berk et al. 2006; Zakamska et al. 2006; Kaviraj et al. 2011).

However, some recent observations have suggested that AGN and starburst activity may not be contemporaneous, even in a statistical sense. Specifically, Davies et al. (2007) study a local sample of AGN at high resolution and see tentative suggestions that strong AGN are not present until the stellar populations in the central \( \lesssim \) 10–100 pc are of the order of a few 10^7 yr old. On large scales, Schawinski et al. (2009) and Wild, Heckman & Charlot (2010) compare the level of AGN activity to the integrated (galaxy-wide or central-kpc, respectively) stellar populations of local galaxies, and suggest that AGN activity may increase after the global stellar populations reach an age of a few 10^8 yr.

Norman & Scoville (1988) suggested that a delay between star formation and AGN activity might result from stellar evolution time-scales if the BH is fuelled directly by stellar winds. At low BH accretion rates (BHARs), this may be important: young stellar populations (\( \lesssim \) 100 Myr) produce fast but tenuous O-star winds, which contribute to a diffuse interstellar medium (ISM) that is hot and/or has large turbulent/bulk motions of \( \gg \) 100 km s\(^{-1}\). If the BHAR is dominated by the accretion of gas from this hot/diffuse phase of the ISM, then the Bondi–Hoyle accretion rate is suppressed by a factor of \( \propto c_{\text{eff}}^3 \), where \( c_{\text{eff}} \) is the effective sound speed and/or turbulent speed in the ISM. As a consequence, if this energy cannot
be efficiently radiated, larger accretion rates will require the arrival of a higher fraction of ‘slow winds’ from more evolved stellar populations, which (having lower velocities and higher densities) can be more easily accreted. A stronger extension to this argument might even be that the energy/momentum feedback in these winds suppresses accretion even of colder gas for some additional time (Wild et al. 2010). There are suggestions that accretion at very low Eddington ratios, $\lesssim 10^{-3} L_{\text{Edd}}$, may be dominated by accretion of diffuse/hot gas, in which case the nature of stellar ejecta could have dramatic effects (Allen et al. 2006; Soria et al. 2006; Hickox et al. 2009).

However, at high accretion rates $\gtrsim 1$ per cent of Eddington, it is generally believed that BHs are accreting from a dynamically cold, discy high-density medium. For example, maser observations have shown typical material at $\sim 1–10$ pc has densities $\gtrsim 10^4$ cm$^{-3}$, with effective temperatures $\lesssim 100$ K and turbulent velocities of $\sim 10–50$ km s$^{-1}$ (Greenhill et al. 2003; Lonsdale et al. 2003; Fruscione et al. 2005; Henkel et al. 2005; Kondratko, Greenhill & Moran 2006, 2008; Nenkova et al. 2008). The cold, discy, dense phase exists in e.g. dense starburst systems on $\sim 100–1000$ pc scales regardless of the presence of extremely young stellar populations (Downes & Solomon 1998; Bryant & Scoville 1999; Tacconi et al. 1999). This is not surprising: tenuous winds will have little dynamical/accelerative effect on cold clouds at these densities, and the gas is believed to be driven in from larger radii, not locally produced by stellar ejecta. For typical conditions, with $\dot{M}_c \sim M_{\text{gas}}$ on scales $\lesssim 10$ pc, the mass/momentum injection rates from O-star winds are much smaller than the inflow rate/gravitational force [for a nuclear star formation rate (SFR) similar to observed values in Davies et al. (2007) and wind momentum loading from Leitherer et al. (1999)]. Moreover, even if the cold medium is replenished or heated by winds, the cooling time in such regions is $\sim 10^5$ times shorter than the dynamical time, so the medium can immediately re-form a cold disc (it retains little memory of the wind properties; see e.g. Schartmann et al. 2010).

In this Letter, we therefore investigate whether ‘delays’ similar to those observed can appear independent of stellar fuelling (or feedback) processes. We show, using a series of high-resolution hydrodynamic simulations, that basic dynamical processes can give rise to qualitatively similar delays even in AGN accreting from cold, dense media.

2 THE SIMULATIONS

Hopkins & Quataert (2010b) give a detailed description of the simulations used here; we briefly summarize some important properties. The simulations were performed with the parallel TreeSPH code GADGET-3 (Springel 2005). They include stellar discs and bulges, dark matter haloes, gas and BHs.

Because of the large dynamic range in both space and time needed for the self-consistent simulation of galactic inflows and nuclear disc formation, we use a ‘zoom-in’ resimulation approach. This begins with a large suite of simulations of galaxy–galaxy mergers, and isolated bar-(un)stable discs. These simulations have $0.5 \times 10^6$ particles, corresponding to a spatial resolution of 50 pc. These simulations have been described in a series of previous papers (Di Matteo, Springel & Hernquist 2005; Cox et al. 2006; Robertson et al. 2006b; Younger et al. 2008; Hopkins et al. 2009).

Following gas down to the BH accretion disc requires much higher spatial resolution than is present in the galaxy-scale simulations. We therefore select snapshots from the galaxy-scale simulations at key epochs and isolate the central 0.1–1 kpc region, which contains most of the gas that has been driven in from large scales.\(^1\) From this mass distribution, we then repopulate the gas in the central regions at much higher resolution, and simulate the dynamics for many local dynamical times. Specifically, we either take the mass distribution in e.g. the central kpc ‘as is’ from the parent distribution (‘cutting out’ the central region and repopulating it with higher resolution particles) or fit it to an exponential disc model which we initialize as an idealized BH/disc/bulge system in equilibrium (to avoid artificial features from the low-resolution initial simulation). These simulations involve $10^7$ particles, with a resolution of a few pc and particle masses of $\sim 10^5$ M$_\odot$. We have run $\sim 50$ such resimulations, corresponding to variations in the global system properties, the model of star formation and feedback, and the exact time in the larger scale dynamics at which the resimulation occurs. Hopkins & Quataert (2010b) present a number of tests of this resimulation approach and show that it is reasonably robust for this problem. This is largely because, for gas-rich discy systems, the central $\sim 300$ pc becomes strongly self-gravitating, generating instabilities that dominate the subsequent dynamics.

These initial resimulations capture the dynamics down to $\sim 10$ pc, still insufficient to quantitatively describe accretion on to a central BH. We thus repeat our resimulation process once more, using the central $\sim 10$–30 pc of the first resimulations to initialize a new set of even smaller scale simulations. These typically have $\sim 10^5$ particles, a spatial resolution of 0.1 pc and a particle mass $\approx 100$ M$_\odot$. We carried out $\sim 50$ such simulations to test the robustness of our conclusions and survey the parameter space of galaxy properties. These final resimulations are evolved for $\sim 10^7$ yr. We also carry out a few extremely high-resolution intermediate-scale simulations, which include $\sim 5 \times 10^7$ particles and resolve structure from $\sim$ kpc to $\lesssim 0.3$ pc, obviating the need for a second zoom-in iteration.

Because of the one-way ‘resimulation’ method adopted here, the small-scale simulations are effectively instantaneous relative to the larger scale simulations. They capture the gas dynamics for one particular realization of the gas distribution on small and large scales, but cannot be evolved for long time-scales relative to the large-scale simulations.

Our simulations include gas cooling and star formation, with gas forming stars at a rate motivated by the observed Kennicut (1998) relation ($\rho_\ast \propto \rho^{-0.5}$). Because we cannot resolve the detailed processes of supernovae explosions, stellar winds and radiative feedback, feedback from stars is modelled with an effective equation of state (Springel & Hernquist 2003). In this model, feedback is assumed to generate a non-thermal (turbulent, in reality) sound speed; we use subgrid sound speeds $\sim 20–100$ km s$^{-1}$, motivated by a variety of observations of dense, star-forming galaxies (Downes & Solomon 1998; Bryant & Scoville 1999; Förster Schreiber et al. 2006; Iono et al. 2007). Within this range, we found little difference in the physics of angular momentum transport or in the resulting BHARs, gas masses, etc. (Hopkins & Quataert 2010b; see also Section 3). Critically, our model does not include any explicit ‘fast stellar winds’ or time dependence in the stellar feedback or mass recycling; there is an effective ISM pressure which corresponds to turbulent ISM sound speeds $<100$ km s$^{-1}$, but this is much less than the $\sim 1000–2000$ km s$^{-1}$ O-star wind velocities and, more importantly, is time-independent. Therefore, any characteristic time-scale that emerges in these simulations is not a consequence of stellar evolution or mass recycling (as we have implemented it), even if this is in reality critical to explaining\(^1\)

\(^1\) Typically $\sim 10^{10}$ M$_\odot$ of gas, within a scalelength of $\sim 0.3–0.5$ kpc.
certain properties of the ISM (see e.g. Hopkins, Quataert & Murray 2011a,b,c).

For all simulations, the total SFR within a given radius is directly determined by integration of the SFR in each gas particle (this is well converged in each case with respect to resolution; see Springel, Di Matteo & Hernquist 2005). The BHAR requires more care. In the nuclear-scale simulations, the BHAR (which we assume is proportional to the AGN luminosity) is taken to be the inflow rate into a radius \(<0.1\) pc. This radius approximately represents the radius where we expect the traditional viscous \(\alpha\)-disc to begin (Goodman 2003), so the further inflow rate should be relatively constant at smaller radii (see the discussion in Hopkins & Quataert 2010b).

In the intermediate- and galaxy-scale simulations, we do not resolve the \(<0.1\) pc radii from which we would like to determine the BHAR (except in our few extremely high-resolution experiments).

We therefore follow Hopkins & Quataert (2010b) and ‘map’ between scales, by taking the smaller scale simulation most closely matched to the inner conditions in our large-scale simulation at each time (within some tolerance) and assuming this is a crude proxy for the average behaviour on small scales given the large-scale conditions (for details, see section 6 of Hopkins & Quataert 2010b).

We do not intend to represent this as a literal ‘zoom-in’ or exactly equivalent to using a single very high-resolution simulation. But using only our ultrahigh resolution simulations (which obviate the need for this mapping) does not change our key qualitative conclusions (but is much noisier and covers a much smaller dynamic range, since there are only a few such simulations).

3 RESULTS

Fig. 1 shows an example of two such simulations, with the BHAR and SFR evaluated on different scales. First, a typical gas-rich major merger simulation (\(f_{\text{gas}} \approx 0.4\) at time of merger, between equal-mass otherwise Milky Way like discs) is shown. We isolate the time near the final coalescence of the two galaxy nuclei, and plot the total SFR within the galaxy and the estimated BHAR. There is a clear offset. The merger drives strong gas inflows into the central kpc which drives the SFR to a peak at just about the time of coalescence. During this time, BH growth is accelerating rapidly, but there is more than enough gas to continue rapid BH growth even after the SFR turns over (i.e. the gas begins to be exhausted). The BHAR finally turns over about \(10^9\) yr later. Secondly, we show one of our nuclear-scale zoom-in simulations, appropriate for the central regions of this simulation near the peak in the BH activity (initial \(f_{\text{gas}} = 0.8\) at small radii with a \(3 \times 10^7 M_{\odot}\) BH: Nf8h1c1dens in Hopkins & Quataert 2010b). We compare the SFR within some small resolved radius \(<20\) pc here), where the inflows have just reached (hence the large initial gas fraction), to the BHAR (gas inflow rate into the central \(<0.1\) pc region). The SFR peaks immediately (more appropriately it would have peaked even slightly before the beginning of this simulation), as it simply traces the gas supply. But the inflows to small radii take some time to become maximal, \(\approx 1\) Myr here.

Fig. 2 extends this to our ensemble of simulations, plotting the delay \(\Delta t\) between the peak of AGN activity and the peak of star formation activity within a given radius \(R\). The points at 0.1–10 pc use just each nuclear-scale simulation individually; those at 100–500 pc use the intermediate-scale simulations (including ultrahigh resolution runs on this scale which do not need another ‘zoom in’ iteration to resolve the BHAR); those at \(>500\) pc use the galaxy-scale simulations. In each case, we measure the total SFR within the annulus plotted, and compare it as a function of time to the estimated BHAR, each smoothed over a time-scale corresponding to a dynamical time at the radius \(R\) (since both are strongly time-variable).\(^2\)

There is a clear delay which is larger when the SFR is measured at larger radii; this arises for two reasons. First, angular momentum loss in gas from gravitational instabilities occurs via transfer to the stellar material, when the magnitude of asymmetries in the potential is sufficient to induce shocks and dissipation in the gas (Hopkins et al. 2009; Hopkins & Quataert 2010b,a). In the limit of a pure gas system, there is no collisionless component to absorb the angular momentum, and so the leading-order angular momentum loss is reduced to second-order resonance effects (Kalnajs 1971) or an effective (turbulent) viscosity (Gammie 2001). To leading order, the efficiency of angular momentum exchange in some annulus scales as \(\alpha(1-f_{\text{gas}})\), where \(f_{\text{gas}} = M_{\text{gas}}/(M_{\text{gas}} + M_*\) is the local gas fraction in the disc (Hopkins & Quataert 2010a).\(^3\) Inflows that

---

\(^2\) The points which correspond to the outermost scales in each tier of simulations should be regarded with some caution, as the characteristic time-scales shown could be influenced by how the simulations were rescaled (since the outer boundary conditions are not necessarily identical to a single, arbitrarily high-resolution simulation). However, the inner regions can be reliably evolved for many dynamical times. We have also compared the values plotted with the results from our more limited suite of extremely high-resolution intermediate-scale simulations that ‘bridge’ multiple scales and obviate the need for rescalings; these are consistent in all cases.

\(^3\) Spherical distributions of material such as the bulge and halo enter in separable fashion.
Within typical starbursts, the gas mass at large radii will continue to increase exponentially until the gas exhaustion time. The Kennicutt–Schmidt relation implies an exhaustion time \( \Delta t(R) \):

\[
\Delta t(R) = \frac{\Sigma_{\text{gas}}}{\epsilon \Sigma_{\text{gas}} t_{\text{syn}}} = e^{-1} t_{\text{dyn}},
\]

where \( \Sigma_{\text{gas}}, \Sigma_{\text{gas}}, t_{\text{syn}} = 1/\Omega = R/V_c \) are the SFR density, gas surface density and orbital frequency, and \( \epsilon \) is the efficiency (fraction of gas turned into stars per dynamical time). Observations suggest values of \( \epsilon \sim 0.006–0.1 \), approximately independent of local density (Krumholz & Tan 2007; Bigiel et al. 2008; Leroy et al. 2008).

We test this scaling in Fig. 2. We compare the measured \( \Delta t(R) \) with a crude estimator of the dynamical time, \( \sim 0.5\text{Myr}/(\text{R}/\text{pc}) \). This is the expectation from our above derivation if the system had a flat rotation curve with \( V_c = 100\text{km}\text{s}^{-1} \) and \( \epsilon \sim 0.02 \). Specific values will depend on the galaxy properties as well as the adopted star formation law (related to the uncertain subgrid star formation law). More directly, we therefore compare with the gas consumption time \( t(G\text{as consumption}) \), where \( t(G\text{as consumption}) \) is defined as the time from when \( f_{\text{gas}} \) peaks within a given annulus (about the peak SFR time) until it falls to \( f_{\text{gas}} < 0.2 \) (the exact value is arbitrary so long as \( f_{\text{gas}} < 1 \); we choose this because it gives about the right normalization). We measure \( \Delta t(t(G\text{as consumption})) \) for each simulation, and plot the distribution of this ratio as a function of \( R \). There is an (unsurprisingly) large scatter at larger radii especially, but this provides a decent approximation to the simulation results.

### 4 DISCUSSION

Simulations of AGN fuelling by gravitational instabilities naturally produce a delay between the time when SFRs peak inside of a given annulus and the time when AGN activity peaks. This offset scales as the gas consumption time, \( \sim 10–100 \) dynamical times. On small scales (\( \lesssim 10\)pc), this is characteristically \( \sim 10^6 \) yr, rising to a few \( \sim 10^8 \) yr on kpc scales. These offsets are similar to the magnitude of time offsets suggested by various observations on both small and large scales (Davies et al. 2007; Schawinski et al. 2009; Wild et al. 2010).

Of course, both the AGN luminosity and SFR are highly time variable (see e.g. Levine, Gnedin & Hamilton 2010). Therefore, this should be taken as a statement only about time-averaged accretion rates and SFRs on a time-scale of at least a few dynamical times. There will be considerable variation from one system to another. And even in a time-averaged sense, the simulations show a range of behaviours, with the magnitude of apparent ‘time offsets’ varying from \( \sim 0.1 \) to 10 times the gas consumption time (on large scales, \( \sim \text{Myr to Gyr time-scales}) \); there are even some systems where the AGN luminosity peaks before the SFR.

Nevertheless, this may be sufficient to account for current observations without invoking poorly understood stellar fuelling (or feedback) processes. Those processes may still be important, of course, and in future work we will investigate how the explicit stellar evolution models presented in Hopkins, Quataert & Murray (2011a,b,c) alter the dynamics discussed here. Observationally testable consequences of these models include the magnitude of time offsets, their scaling with radii and the dynamical time of the galaxy, and the scaling of AGN activity with gas fraction inside...
some radius. Since it is gas fraction that drives these effects, one does not expect to see evidence for AGN – on average – reaching their peak luminosity while the gas fraction on large scales is very large \( f_{\text{gas}} \approx 1 \), but rather expects to see that the ‘delayed’ peak in AGN activity corresponds to systems with \( f_{\text{gas}} \lesssim 0.1\text{–}0.5 \). And there is some observational evidence from metal enrichment and stellar age profiles that high gas densities and star formation proceed ‘outside-in’ in similar fashion to that predicted here in the early stages of mergers (Kewley et al. 2010; Rupke, Kewley & Barnes 2010; Soto & Martin 2010; Torrey et al. 2011).

This also has important implications for AGN feedback models. AGN luminosities in realistic hydrodynamic models do not peak at the same time as the gas density on small scales, but rather at somewhat later times when most of the gas has been exhausted by star formation and/or expelled by stellar feedback. To the extent that AGN feedback assists in the ‘blowout’ of gas (shutting down star formation), it primarily sweeps up the ‘trickle’ of remaining gas that would provide for low-level star formation over the next few Gyr, not the bulk of the galaxy gas supply (see e.g. Hopkins et al. 2008c,b). For the simulations shown here, it has been shown previously that the AGN feedback actually acts on a very small residual amount of gas, and has a nearly negligible effect on the peak SFR nuclear starburst (see Cox et al. 2006; Robertson et al. 2006a; Hopkins, Cox & Hernquist 2008a). Similar conclusions have recently been obtained using entirely different accretion and AGN feedback models (Debuhr et al. 2010). But this may be needed to explain the rapid colour evolution of galaxies through the ‘green valley’ (see e.g. Kaviraj et al. 2011).

This also means that galaxies at their peak in star formation activity may not necessarily be ideal places to look for the effects of AGN feedback. Indeed, observations of such systems have found mixed results (see e.g. Rupke, Veilleux & Sanders 2005; Veilleux, Cecil & Bland-Hawthorn 2005; Krug, Rupke & Veilleux 2010, and references therein). Post-starburst (Tremonti, Moustakas et al. 2004, AJ, 136, 2782) or later stage, AGN-dominated mergers (Bautista et al. 2010; Dunn et al. 2010; Feruglio et al. 2010; Humphrey et al. 2010; Sturm et al. 2011) might be more promising.

Acknowledgments

We thank Vivienne Wild, Kevin Schawinski, Ric Davies and Tim Heckman for helpful discussions that inspired this manuscript. We also thank the anonymous referee for a number of thoughtful suggestions.

References

Allen S. W. et al., 2006, MNRAS, 372, 21
Aller M. C., Richstone D. O., 2007, ApJ, 665, 120
Bautista M. A. et al., 2010, ApJ, 713, 25
Bigiel F. et al., 2008, AJ, 136, 2846
Brotherton M. S. et al., 1999, ApJ, 520, L87
Bryant P. M., Scoville N. Z., 1999, AJ, 117, 2632
Canalizo G., Stockton A., 2001, ApJ, 555, 719
Coil A. L. et al., 2011, ApJ, 743, 46
Cox T. J. et al., 2006, ApJ, 650, 791
Davies R. I. et al., 2007, ApJ, 671, 1388
Debuhr J. et al., 2010, MNRAS, 406, L55
Di Matteo T., Springel V., Hernquist L., 2005, Nat, 433, 604
Downes D., Solomon P. M., 1998, ApJ, 507, 615
Dunn J. P. et al., 2010, ApJ, 709, 611
Feoli A., Mancini L., 2009, ApJ, 703, 1502
Ferrarese L., Merritt D., 2000, ApJ, 539, L9
Feruglio C. et al., 2010, A&A, 518, L155
Fürster Schreiber N. M. et al., 2006, ApJ, 645, 1062
Fruscione A. et al., 2005, ApJ, 624, 103
Gammie C. F., 2001, ApJ, 553, 174
Gebhardt K. et al., 2000, ApJ, 539, L13
Goodman J., 2003, MNRAS, 339, 937
Greenhill L. J. et al., 2003, ApJ, 590, 162
Henkel C. et al., 2005, A&A, 436, 75
Hickox R. C. et al., 2009, ApJ, 696, 891
Hopkins P. F., Quataert E., 2010a, MNRAS, 415, 1027
Hopkins P. F., Quataert E., 2010b, MNRAS, 407, 1529
Hopkins P. F. et al., 2007, ApJ, 669, 67
Hopkins P. F., Cox T. J., Hernquist L., 2008a, ApJ, 689, 17
Hopkins P. F. et al., 2008b, ApJS, 175, 390
Hopkins P. F. et al., 2008c, ApJS, 175, 356
Hopkins P. F. et al., 2009, ApJ, 691, 1168
Hopkins P. F., Quataert E., Murray N., 2011a, MNRAS, 417, 950
Hopkins P. F., Quataert E., Murray N., 2011b, MNRAS, preprint (arXiv:1110.4636)
Hopkins P. F., Quataert E., Murray N., 2011c, MNRAS, preprint (arXiv:1110.4638)
Hopkins P. F., Quataert E., Murray N., 2011d, MNRAS, 415, 289
Hopkins P. F., Quataert E., Murray N., 2011e, MNRAS, 415, 3798
Kennicutt R. C., Jr., 1998, ApJ, 498, 541
Kewley L. J. et al., 2010, ApJ, 721, L48
Kondratko P. T., Greenhill L. J., Moran J. M., 2006, ApJ, 652, 136
Kondratko P. T., Greenhill L. J., Moran J. M., 2008, ApJ, 678, 87
Krug H. B., Rupke D. S. N., Veilleux S., 2010, ApJ, 708, 1145
Krumholz M. R., Tan J. C., 2007, ApJ, 654, 304
Leitherer C. et al., 1999, ApJS, 123, 3
Leroy A. K. et al., 2008, AJ, 136, 2782
Levine R., Gnedin N. Y., Hamilton A. J. S., 2010, ApJ, 716, 1386
Lonsdale C. J. et al., 2003, ApJ, 592, 804
Magorrian J. et al., 1998, AJ, 115, 2285
Merloni A., Rudnick G., Di Matteo T., 2004, MNRAS, 354, L37
Nenkova M. et al., 2008, ApJ, 685, 160
Norman C., Scoville N., 1988, ApJ, 332, 124
Robertson B. et al., 2006a, ApJ, 641, 21
Robertson B. et al., 2006b, ApJ, 641, 90
Rupke D. S., Veilleux S., Sanders D. B., 2005, ApJ, 632, 751
Rupke D. S. N., Kewley L. J., Barnes J. E., 2010, ApJ, 710, L156
Sánchez S. F. et al., 2004, ApJ, 614, 586
Sanders D. B., 1999, ApJS, 266, 312
Schawinski K. et al., 2009, ApJ, 692, L19
Soria R. et al., 2006, ApJ, 640, 143
Soto K. T., Martin C. L., 2010, ApJ, 716, 332
Springel V., 2005, MNRAS, 364, 1105
Springel V., Hernquist L., 2003, MNRAS, 339, 289
Springel V., Di Matteo T., Hernquist L., 2005, MNRAS, 361, 776
Sturm E. et al., 2011, ApJ, 733, L16
Tacconi L. J. et al., 1999, ApJ, 524, 732
Torrey P. et al., 2011, ApJ, preprint (arXiv:1107.0001)
Tremonti C. A., Moustakas J., Diamond-Stanic A. M., 2007, ApJ, 663, L77
Vanden Berk D. E. et al., 2006, AJ, 131, 84
Veilleux S., Cecil G., Bland-Hawthorn J., 2005, ARA&A, 43, 476
Wild V. et al., 2009, MNRAS, 395, 144
Wild V., Heckman T., Charlot S., 2010, MNRAS, 405, 933
Younger J. D. et al., 2008, ApJ, 686, 815
Zakamska N. L. et al., 2006, AJ, 132, 1496

This paper has been typeset from a TeX/LaTeX file prepared by the author.