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Resolving the generation of starburst winds in Galaxy mergers

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ABSTRACT

We study galaxy superwinds driven in major mergers, using pc-scale resolution simulations with detailed models for stellar feedback that can self-consistently follow the generation of winds. The models include molecular cooling, star formation at high densities in giant molecular clouds, and gas recycling and feedback from supernovae (I and II), stellar winds and radiation pressure. We study mergers of systems from Small-Magellanic-Cloud-like dwarfs and Milky Way analogues to \( z \sim 2 \) starburst discs. Multiphase superwinds are generated in all passages, with outflow rates up to \( \sim 1000 \) M\( \odot \) yr\(^{-1} \). However, the wind mass-loading efficiency (outflow rate divided by star formation rate, SFR) is similar to that in the isolated galaxy counterparts of each merger: it depends more on global galaxy properties (mass, size and escape velocity) than on the dynamical state or orbital parameters of the merger. Winds tend to be bi- or unipolar, but multiple ‘events’ build up complex morphologies with overlapping, differently oriented bubbles and shells at a range of radii. The winds have complex velocity and phase structure, with material at a range of speeds up to \( \sim 1000 \) km s\(^{-1} \) (forming a Hubble-like flow), and a mix of molecular, ionized and hot gas that depends on galaxy properties. We examine how these different phases are connected to different feedback mechanisms. These simulations resolve a problem in some ‘subgrid’ models, where simple wind prescriptions can dramatically suppress merger-induced starbursts, often making it impossible to form Ultra Luminous Infrared Galaxies (ULIRGs). Despite large mass-loading factors (\( \gtrsim 10–20 \)) in the winds simulated here, the peak SFRs are comparable to those in ‘no wind’ simulations. Wind acceleration does not act equally, so cold dense gas can still lose angular momentum and form stars, while these stars blow out gas that would not have participated in the starburst in the first place. Considerable wind material is not unbound, and falls back on the disc at later times post-merger, leading to higher post-starburst SFRs in the presence of stellar feedback. We consider different simulation numerical methods and their effects on the wind phase structure; while most results are converged, we find that the existence of small clumps in the outflow at large distances from the galaxy is quite sensitive to the methodology.

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

1 INTRODUCTION

It is well established that feedback from stars is a key component of galaxy formation models. Absent strong stellar feedback, gas in cosmological models quickly cools and turns into stars, predicting galaxies with much larger stellar masses than observed (e.g. Katz, Weinberg & Hernquist 1996; Somerville & Primack 1999; Cole et al. 2000; Springel & Hernquist 2003b; Kereš et al. 2009, and references therein). ‘Slowing down’ star formation (SF) does not eliminate this problem; the real issue is that the amount of baryons in real galactic discs is much lower than the universal baryon fraction,
which is the predicted amount of gas and stars found in cosmological simulations of low-mass galaxies without strong feedback (White & Frenk 1991; for a recent review see Kereš et al. 2009). Observational constraints from intergalactic medium (IGM) enrichment further make clear that many of those baryons must have at one point entered galaxy haloes and discs, and been enriched, then ejected (Aguirre et al. 2001; Pettini et al. 2003; Songaila 2005; Martin et al. 2010). Galactic superwinds are therefore implied, with large mass-loading factors of several times the star formation rate (SFR) that are required in cosmological simulations to reproduce these observations (e.g. Oppenheimer & Davé 2006). Such mass-loading factors are also observationally inferred in many local galaxies and massive star-forming regions at $z \sim 2$–3 (Martin 1999, 2006; Heckman et al. 2000; Sato et al. 2009; Chen et al. 2010; Steidel et al. 2010; Coil et al. 2011; Newman et al. 2012).

Until recently, however, numerical simulations have generally been unable to produce, from an a priori model, winds with large mass-loading factors (as well as a plausible scaling of wind mass loading with galaxy mass or other properties); this is especially true of models which include only thermal or ‘kinetic’ feedback via supernovae (SNe), which is very inefficient in the dense regions where SF occurs (see e.g. Guo et al. 2010; Nagamine 2010; Bournaud et al. 2011; Brook et al. 2011; Powell, Slyz & Devriendt 2011, and references therein). More recent simulations have, with higher resolution and/or stronger feedback prescriptions, seen strong winds, but generally find that it is critical to include (usually simplified) prescriptions for cooling suppression and/or ‘pre-supernova’ feedback (see Governato et al. 2010; Macciò et al. 2012; Teyssier et al. 2013). This should not be surprising: feedback processes other than SNe are critical for supressing SF in dense gas; these include protostellar jets, H ii photoionization, stellar winds and radiation pressure from young stars. Including these mechanisms self-consistently maintains a reasonable fraction of the interstellar medium (ISM) at densities where the thermal heating from SNe has a larger effect; moreover, there are many regimes where these mechanisms can directly drive winds, independent of and with greater mass loading than SNe.

This conclusion implies that (not surprisingly) an accurate treatment of galactic winds requires a more realistic treatment of the stellar feedback processes that maintain the multiphase structure of the ISM of galaxies. Motivated by these problems, in Hopkins, Quataert & Murray (2011, Paper I) and Hopkins, Quataert & Murray (2012a, Paper II), we developed a new set of numerical models to follow feedback on small scales in giant molecular clouds (GMCs) and star-forming regions, in simulations with pc-scale resolution. These simulations include the momentum imparted locally (on sub-GMC scales) from stellar radiation pressure, radiation pressure on larger scales via the light that escapes star-forming regions, H ii photoionization heating, as well as the heating, momentum deposition, and mass-loss by SNe (Type I and Type II) and stellar winds [O star and asymptotic giant branch (AGB)]. The feedback is tied to the young stars, with the energetics and time dependence taken directly from stellar evolution models. Our models also include cooling to temperatures <100 K, and a treatment of the molecular/atomic transition in gas and its effect on SF (following Krumholz & Gnedin 2011). We showed that these feedback mechanisms produce a quasi-steady ISM in which GMCs form and disperse rapidly, after turning just a few per cent of their mass into stars. This leads to an ISM with phase structure, turbulent velocity dispersions, scaleheights and GMC properties (mass functions, sizes, scaling laws) in reasonable agreement with observations.

In Hopkins, Quataert & Murray (2012b, Paper III), we show that these same models of stellar feedback predict the elusive winds invoked in almost all galaxy formation models; the combination of multiple feedback mechanisms is critical to give rise to massive, multiphase winds having a broad distribution of velocities, with material both stirred in local fountains and unbound from the disc.

However, in Paper III we examine only idealized isolated disc galaxies. Although this is probably representative of much of a galaxy’s lifetime, a great deal of observational study has focused on winds in ‘starburst’ galaxies, often in interacting or merging systems. Indeed, a wide range of phenomena indicate that gas-rich mergers are important to galaxy formation and SF. These systems dominate the most intense starburst populations: Ultra Luminous Infrared Galaxies (ULIRGs) at low redshift (Joseph & Wright 1985; Sanders & Mirabel 1996), and hyper-LIRGs and bright submillimetre galaxies at high redshifts (Papovich et al. 2005; Tacconi et al. 2006, 2008; Schinnerer et al. 2008; Younger et al. 2008b; Chapman et al. 2009). They are powered by compact concentrations of gas at enormously high densities (Scoville et al. 1986; Sargent et al. 1987), which provides material to fuel black hole (BH) growth and boost the concentration and central phase-space density of merging discs to match those of ellipticals (Hernquist, Spergel & Héyl 1993; Robertson et al. 2006; Hopkins et al. 2008c). Various studies have shown that the mass involved in these starburst events is critical for explaining the relations between spirals, mergers and ellipticals, and has a dramatic impact on the properties of merger remnants (e.g. Lake & Dressler 1986; Doyon et al. 1994; Shier & Fischer 1998; James et al. 1999; Genzel et al. 2001; Tacconi et al. 2002; Rothberg & Joseph 2004, 2006; Dasyra et al. 2006, 2007; Hopkins et al. 2009a,b).

With central densities as large as ~1000 times those in Milky Way (MW) GMCs, these systems also provide a laboratory for studying SF; the ISM and the generation of galactic winds under the most extreme conditions. In Hopkins et al. (2013a, Paper IV), we therefore extend the models from Paper I–Paper III to include major galaxy mergers. We showed there that the same feedback mechanisms can explain the self-regulation of starbursts and extension of the Kennicutt–Schmidt relation to the highest gas surface densities observed. We also show how this controls the SFRs and their spatial distributions, the formation of clusters, and the formation and destruction of GMCs in the ISM. In this paper, we further investigate the phase structure and generation of galactic superwinds in these models, and how they relate to merger dynamics and SF histories.

2 METHODS

The simulations analysed in this paper are presented in Paper IV. We therefore only briefly summarize their most important properties here, and refer interested readers to that paper for the simulation details.

The simulations follow the methodology and galaxy models originally presented in Paper I (section 2 and tables 1–3) and Paper II (section 2), using a heavily modified version of the TreeSPH code gadget-3 (Springel 2005), in its fully conservative ‘density–entropy’ form (Springel & Hernquist 2002). They include stars, dark matter and gas (with cooling, SF and stellar feedback).

1 Movies of these simulations are available at http://www.tapir.caltech.edu/~phopkins/Site/Movies_swng.html
2.1 Initial conditions

We consider mergers of four initial disc models spanning a range of galaxy types. Each has a bulge, stellar and gas disc, halo and central BH. At our standard resolution, each model has $\approx 0.3-1 \times 10^6$ total particles, giving particle masses of $500-1000 M_\odot$ and 1–5 pc smoothing lengths. Convergence tests of isolated versions of these discs have been extended to $\approx 10^7$ particles and sub-pc resolution.

The disc models include:

1. Small Magellanic Cloud (SMC): an SMC-like dwarf, with baryonic mass $M_{\text{bar}} = 8.9 \times 10^7 M_\odot$ and halo mass $M_{\text{halo}} = 2 \times 10^{10} M_\odot$ (concentration $c = 15$), a Hernquist (1990) profile bulge with a mass $m_b = 10^7 M_\odot$, and exponential stellar ($m_\star = 1.3 \times 10^9 M_\odot$) and gas discs ($m_g = 7.5 \times 10^8 M_\odot$) with scalelengths $h_d = 0.7$ and $h_g = 2.1$ kpc, respectively. The initial stellar scaleheight is $z_0 = 140$ pc and the stellar disc is initialized such that the Toomre $Q = 1$ everywhere.

2. MW: an MW-like galaxy, with halo and baryonic properties of $(M_{\text{halo}}, c) = (1.6 \times 10^{12} M_\odot, 12)$ and $(M_{\text{bar}}, m_b, m_\star, m_g) = (7.1, 1.5, 4.7, 0.9) \times 10^9 M_\odot, Z = Z_\odot$ and scalelengths/heights $(h_d, h_g, z_0) = (3.0, 6.0, 0.3) \text{kpc}$ (note that the gas disc is more extended than the stellar disc, giving a gas fraction $\approx 10$ per cent inside the solar circle).

3. Sbc: an LIRG-like galaxy (i.e. a more gas-rich spiral than is characteristic of those observed at low redshifts) with $(M_{\text{halo}}, c) = (1.5 \times 10^{11} M_\odot, 11)$, $(M_{\text{bar}}, m_b, m_\star, m_g) = (10.5, 1.0, 4.0, 5.5) \times 10^9 M_\odot, Z = 0.3 Z_\odot$ and $(h_d, h_g, z_0) = (1.3, 2.6, 0.13) \text{kpc}$. (HIz: a high-redshift massive starburst disc, chosen to match the properties of the observed non-merging but rapidly star-forming SMG population, with $(M_{\text{halo}}, c) = (1.4 \times 10^{12} M_\odot, 3.5)$ and a virial radius appropriately rescaled for a halo at $z = 2$ rather than $z = 0$, $(M_{\text{bar}}, m_b, m_\star, m_g) = (10.7, 0.7, 3.7) \times 10^9 M_\odot, Z = 0.5 Z_\odot$ and $(h_d, h_g, z_0) = (1.6, 3.2, 0.32) \text{kpc}$.)

We consider equal-mass mergers of identical copies of galaxies (1)–(4), on parabolic orbits with two representative choices for the initial disc orientations. The first (orbit $e$ in Cox et al. 2006b) is near-prograde (a strong resonant interaction) and the second (orbit $f$) is near-retrograde (or polar-retrograde, a weak out-of-resonance interaction). For the most relevant properties of stellar winds, there is little difference between these orbits which bracket the range from most to least violent encounters; we therefore expect the properties examined here to be robust over a wide range of configurations.

2 To isolate the effects of stellar feedback, models for BH growth and feedback are disabled here.

3 These are typical smoothing lengths in the dense gas; generally the smoothing lengths evolve adaptively following Springel & Hernquist (2002) to enclose a fixed number $\approx 128$ neighbours. The gravitational softening lengths are set to be approximately equal to the minimum smoothing lengths.

4 These tests are described in Paper I and Paper II, and used to check convergence in small-scale ISM properties. We have also run every simulation described in this paper with 10 times fewer particles (2 times larger softening/smoothing); although some small-scale properties differ, our conclusions regarding quantities considered in this paper are identical. Additional numerical tests of the smoothed particle hydrodynamics (SPH) method, relevant primarily for the wind phase structure in the extended halo, are presented in Appendix A.

5 The scaleheight is set to be $=0.2$ times the scalelength. Since the initial mass of stars is small, this has little effect, and most new stars form with a somewhat larger scaleheight; see Paper II (fig. 9) for further discussion.

2.2 Cooling and feedback

Gas follows an atomic cooling curve with additional fine-structure cooling to $\sim 10$ K. SF is allowed only in dense, molecular, self-gravitating regions above $n > 1000 \text{cm}^{-3}$. We follow Krumholz & Gnedin (2011) to calculate the molecular fraction in dense gas as a function of local column density and metallicity, and follow Hopkins, Quataert & Murray (2013c) to calculate the local virial parameter of the gas (in order to restrict SF to gas which is locally self-gravitating). This then forms stars at a rate $\rho_* = \rho_\text{halo}/t_g$; however, the average efficiency on larger scales is much lower because of feedback.

Once stars form, their feedback effects are included from several sources.

1. Momentum flux from radiation pressure, SNe and stellar winds. Gas surrounding stars receives a direct momentum flux $P = P_{\text{SN}} + P_\text{w} + P_{\text{rad}}$, where the separate terms represent the direct momentum flux of SN ejecta, stellar winds and radiation pressure. The first two are directly tabulated for a single stellar population as a function of age and metallicity $Z$ and the flux is directed away from the star. The latter is approximately $P_{\text{rad}} \approx (1 + \tau_{\text{IR}}) L_{\text{incident}}/c$, where $L_{\text{incident}}$ accounts for the absorption of the initial UV/optical flux and multiple scatterings of the IR flux if the region between star and gas particle is optically thick in the IR.

2. SN ejecta and Shock heating. Gas shocked by SNe can be heated to high temperatures. We tabulate the SN Type I and Type II rates from Mannucci, Della Valle & Panagia (2006) and STAR-BURST99, respectively, as a function of age and metallicity for all star particles and stochastically determine at each timestep if an SN occurs. If so, the appropriate mechanical luminosity is injected as thermal energy in the gas within a smoothing length of the star particle, along with the relevant mass and metal yield.

3. Gas recycling and shock heating in stellar winds. Similarly, stellar winds are assumed to shock locally and so we inject the appropriate tabulated mechanical power $L(t, Z)$, mass and metal yields, as a continuous function of age and metallicity into the gas within a smoothing length of the star particles. The integrated mass fraction recycled is $\sim 0.3$.

4. Photoheating of H II regions and photoelectric heating. We also tabulate the rate of production of ionizing photons for each star particle; moving radially outwards from the star, we then ionize each neutral gas particle until the photon budget is exhausted. Ionized gas is maintained at a minimum $\approx 10^8$ K until it falls outside an H II region. Photoelectric heating is followed in a similar manner using the heating rates from Wolfire et al. (1995).

6 In Paper I and Paper II, we show that the galaxy structure and SFR are basically independent of the small-scale SF law, because they are feedback regulated. For example, we have re-run lower resolution tests with a simpler prescription where SF is restricted to all gas with $n > 1000 \text{cm}^{-3}$, and find that it makes little difference except to ‘smear out’ the SFR in dense regions. As a result, this choice also has little effect on the winds studied here.

7 Photons which escape the local stellar vicinity can be absorbed at larger radii. Knowing the intrinsic spectrum of each star particle, we attenuate integrating the local gas density and gradients to convergence, and propagate the resulting ‘escaped’ flux to large distances. This can then be used to calculate the local incident flux on all gas particles, from which local absorption is calculated by integrating over a frequency-dependent opacity that scales with metallicity. The appropriate radiation pressure force is then imparted.
Extensive numerical tests of the feedback models are presented in Paper II. All energy, mass and momentum-injection rates are taken from the stellar population models in STARBURST99, assuming a Kroupa (2002) initial mass function (IMF), without free parameters.

3 OUTFLOW MORPHOLOGIES

For reference, Fig. 1 shows the stellar morphology as it would be optically observed with ideal resolution during a representative stage of the merger simulations, when all feedback mechanisms are present (the image is a mock u/g/r composite calculated as described in Paper IV).

In this paper, we are interested in the structure of the outflows during the mergers. This is shown in Fig. 2. Here we show the projected gas density with colours encoding the gas temperature. The projected temperatures are logarithmically averaged and surface density weighted, so reflect the temperature of most of the line-of-sight gas mass, rather than the temperature that contains most of the thermal energy.

Outflows are plainly evident; we will quantify their properties and phase distribution in detail below. Briefly, on small scales the simulated ISM is a supersonically turbulent medium (see Hopkins 2013a,b) in which cold GMCs continuously form and are dispersed by feedback after turning a few per cent of their mass into stars (see Paper II, Paper IV). The subgalactic structure is qualitatively similar to that seen in other simulations with similar resolution and explicit treatment of the cold gas (e.g. Bournaud et al. 2011), albeit with some significant differences owing to which feedback mechanisms are or are not included (for a detailed comparison, see Paper IV). There is volume-filling hot gas (heated by SNe and O-star winds), which vents an outflow component; occasionally the early stages are evident as ‘bubbles’ breaking out of the warm-phase gas. Warm/cold gas is mixed throughout the outflow, especially near the galaxy (before they have had time to mix with the more diffuse material); these are sometimes entrained by the hot gas but more often directly accelerated by radiation pressure. Qualitatively, this is true in isolated galaxies as well (Paper III).

In Fig. 2, successive generations of ‘bursts’ and strong outflows are evident as overlapping shells (many caused by shocks as different ejection events ‘catch up’); these are each broadly associated with a galaxy passage. The diffuse hot gas, being volume-filling, has a near-unity covering factor, but it is still clearly organized into various ‘bubbles’. Each of these has a broadly bimodal morphology set by much of the hot gas blowing out perpendicular to the disc along the path of least resistance. Since the disc orientations change during the merger owing to gravitational torques, the successive bursts have different orientations. At the largest radii, the diffuse gas cools adiabatically; this would not necessarily occur with a realistic IGM present into which the hot gas could propagate. The warm and cool gas also has a significant (albeit smaller) covering factor even at $\geq 100$ kpc (except in the MW model). However, the morphology is much less smooth – this gas is primarily in filaments and shells. Although the crude average distribution of these is similar to the hot gas, there is much larger line-of-sight variation. Some (but not all) of this material is accelerated by radiation pressure, and so tends to reach somewhat lower velocities than the hottest pressure-accelerated gas, and therefore the density falls off proportionally more rapidly at very large radii (although, being more dense, this material may be able to propagate ballistically into the IGM where lower density, volume-filling material would be halted by the ambient pressure). In any case, as we discuss in detail in Paper III and Section 8, the outflows should not be taken too literally at the largest radii: we do not include initial gaseous haloes or a realistic IGM into which the wind should propagate, so the winds here expand unimpeded beyond the halo.

X-ray observations provide a strong probe of the hot phase of the galactic winds; Fig. 3 therefore shows the same images, but now in their approximate X-ray properties. For convenience, rather than making a detailed mock observation corresponding to a given instrument, sensitivity, redshift and energy range, we instead quantify the approximate X-ray emission with the sum of the thermal bremsstrahlung emission (emissivity per unit volume $\propto T_{\text{gas}}^2 n_e n_i$) and the metal cooling luminosity [using the compiled tables in Wiersma, Schaye & Smith (2009) as a function of $n_i$, $n_e$, Z and $T_{\text{gas}}$, assuming solar abundance ratios

\begin{figure}[h]
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\includegraphics[width=0.5\textwidth]{figure1.png}
\caption{Morphology of a standard simulation (all feedback mechanisms included) of a merger of the HiZ disc model (a massive, $z \sim 2$–4 starburst disc merger). The time is near apocentre after first passage. The image is a mock u/g/r (SDSS-band) composite, with the spectrum of all stars calculated from their known age and metallicity, and dust extinction/reddening accounted for from the line-of-sight dust mass. The brightness follows a logarithmic scale with a stretch of $\sim 2$–4. Young star clusters are visible throughout the system as bright white pixels. The nuclei contain most of the SF, but considerable fine structure in the dust and gas gives rise to complicated filaments, dust lanes and patchy obscuration of star-forming regions.}
\end{figure}

\footnote{We caution that the very small, cold ‘clumps’ at large radii in the wind (distinct from the resolved molecular clouds in the disc and the coherent warm/cold shells and filaments in outflow) are only marginally resolved and are probably an artefact of the numerical method used, in concert with the fact that there is no cosmic ionizing background present in these simulations to heat gas far from the galaxy. In Appendix A, we re-run a limited subset of our simulations with an alternative formulation of SPH designed to treat contact discontinuities more accurately, and include UV background heating, and show that these largely disappear. We will focus in this paper only on results robust to our resolution and numerical method, but direct the interested reader to Appendix A and Hopkins (2013) for more details.}
Figure 2. Images of the gas in the starburst-driven superwinds in our simulations. Brightness encodes projected gas density (increasing with density; logarithmically scaled with an ≈4 dex stretch); colour encodes gas temperature with the blue/white material being $T \lesssim 1000$ K cold atomic/molecular gas, pink $\sim 10^4$–$10^5$ K warm ionized gas and yellow $\gtrsim 10^6$ K hot gas. We show just one example of each merger, but the $e$ and $f$ orbits are similar in each case. For each, we show the image at a fixed time near the starburst and at various spatial scales. A massive wind is plainly evident; the winds are multiphase with volume-filling hot gas and ejected streams/shells of cold gas. We caution that the formation of the small, marginally resolved isolated ‘blobs’ of cold gas within the hot background outflow (not the warm/cold shells or GMCs within the disc) is quite sensitive to the numerical details of the simulations (see footnote 8 in the text). A large fraction is unbound and escapes the galaxy halo. In the MW case, the gas-poor nature of the merger means the wind is almost entirely ‘hot’; in the Sbc and HiZ cases a much larger fraction of ejected material is warm/cool; in the SMC case there is a broad mix of warm gas and hot gas ejected. The shells and features in the diffuse gas arise from multiple bursty episodes shocking as they ‘catch up’ to one another.

and the $z = 0$ ionizing background]. Note that these can include significant contributions from low-temperature gas, so this need not refer specifically to X-ray observations. Broadly, the morphology is similar, but with the hot, low-density material highlighted, the various bubbles and shells are more obvious. It is also clear, as we go to larger scales, that the larger/older bubbles have distinct orientations, corresponding to the orientation of the galaxies at earlier merger stages.

4 PHASE STRUCTURE: HOT X-RAY HALOES AND COLD MOLECULAR GAS

In Paper II, we discuss in great detail the phase structure and density distribution of the ISM; here, we examine whether the same results are obtained in mergers. Fig. 4 plots the density probability density function (PDF) of the ISM, i.e. mass per logarithmic interval in $n$. For clarity, we just show the $f$ models, but the $e$ models are
Figure 3. Galactic wind thermal + metal line emission morphology, as a proxy for X-ray emission (though we caution that this includes gas with a broad range of temperatures). The maps show the images as in Fig. 2, but in a single-colour scale where intensity encodes the projected bremsstrahlung emissivity plus metal cooling luminosity [again we caution that the small clumps at large radii may be artificial (see footnote 8 in the text)]. Since this weights the volume-filling hot gas, the different bubbles and shells are more clear. At each scale, clear changes in the orientation of the older/larger bubbles are also evident.
Figure 4. Density distribution of different ISM phases, for different galaxy disc models (Sbc, MW and SMC), averaged over the duration of the merger. Top: mass-weighted density PDF \( \frac{d m_{\text{gas}}}{d \log n} \), i.e. the mass fraction per logarithmic interval in density \( n \). We show the distribution for all gas in the simulation (black), the gas approximately within the (multiphase) star-forming discs (blue), the gas in the extended, ionized discs and halo (green) and wind/outflow material (orange). These trace the material at high, intermediate and low densities, respectively (as expected). Each density PDF has a very broad density distribution. Middle: mass-weighted density PDF within the ‘star-forming discs’. We show the density PDF for all of the gas in the region (black), the ‘cold’ phase \( (T < 2000 \text{ K}) \), the ‘warm ionized’ phase \( (2000 < T < 4 \times 10^5 \text{ K}) \) and the ‘hot diffuse’ phase \( (T > 4 \times 10^5 \text{ K}) \). Most of the mass is in the cold phase (which dominates at high densities), but with a comparable contribution from the warm medium (the hot phase contributing a few per cent). The multimodal nature of the total density PDF is a consequence of the strong phase separation. Note that since these simulations do not include the cosmic ionizing background, we truncate the cold-phase distribution at densities below which post-processing calculations suggest that it would be photoionized \( (\sim 0.01 \text{ cm}^{-3}) \); see Faucher-Giguère et al. 2008; Hopkins et al. 2013). Such gas contributes negligibly to the total at very low densities, in any case. Bottom: volume-weighted density PDF \( \frac{d V_{\text{gas}}}{d \log n} \) for the star-forming disc. The hot diffuse phase dominates, with a moderate volume-filling fraction for the warm phase and a small \( (\sim 1–5 \text{ per cent}) \) volume-filling fraction of cold molecular clouds in the disc.

Fig. 5 shows how this compares (over the course of the merger) to the isolated discs. We show one example but the results are similar in each case. We plot the density distribution by temperature phase for all gas, averaged over the run of the isolated disc simulation (in which it reaches a steady state, so is nearly time independent), averaged over the merger duration, and at the snapshot with the peak SFR (near final coalescence) in the merger. Averaged over the merger, there is little difference (some material is at lower densities simply because the winds have more time to ‘escape’, and slightly more material is at high densities). This reflects the well-known fact that in merger simulations, most of the time (and most of the SF) is contributed by the ‘isolated mode’, namely the separate SF in the two discs as they orbit between passages, rather than the merger-induced ‘burst’ on top of this (which only dominates the central \( \sim 1 \text{ kpc} \) seen in Paper IV; see also Cox et al. 2008; Hopkins & Hernquist 2010). During the peak starburst, the results are still qualitatively similar (especially for the warm/hot gas); the peak density associated with each phase is also the same. The main difference is that a fraction of the gas funnelled into the galaxy centres is pushed to much higher densities \( n \gg 10^4 \text{ cm}^{-3} \) where it rapidly turns into stars. Although we stress that this is still not most
of the gas (even the dense molecular gas). This is very different from models with weak/no feedback, which see catastrophic runaway to arbitrarily high densities \( n \sim 10^9 \) for most of the star-forming gas, in contrast to observations which show that most of the gas in GMCs and other dense regions is at modest, non-star-forming densities (e.g. Williams & McKee 1997; Evans 1999, and references therein).

The increase in gas at the highest densities during the starburst would be evident in dense molecular traces, as discussed in Narayanan et al. (2006) and Hopkins et al. (2013b). Specifically, if we adopt the simple conversions therein from mass above \( 10^3 \text{ cm}^{-3} \) to HCN luminosity and mass above \( 100 \text{ cm}^{-3} \) to CO(1–0) luminosity, we estimate that the ratio \( L_{\text{HCN}}/L_{\text{CO}(1–0)} \) should increase from \( \approx 0.02 \) in the isolated case (presented therein) to \( \approx 0.15–0.30 \) in the peak of the merger. This is consistent with what is seen in real local ULIRGs, essentially all of which are late-stage major mergers, in the compilation of Gao & Solomon (2004), Narayanan, Cox & Hernquist (2008) and Juneau et al. (2009).

In Fig. 6 we show the phase distribution of the winds, similar to Fig. 4. These are discussed in detail for the isolated cases in Paper III. We compare the distribution of temperatures weighted by their contribution to thermal bremsstrahlung plus metal cooling emission (as described above) for all the gas, in different outflow velocity intervals. We also plot the velocity distribution of all gas (mass per radial outflow velocity \( v_r \)), the ‘peak’ near \( v_r = 0 \) being the non-wind material (with the wind evident in the large tail). And we show the density distribution of the wind material specifically, in the style of Fig. 4. The velocity distributions are wide (discussed below). The inhomogeneous morphologies of the winds are reflected in the broad phase and density distribution (though recall the numerical caveats regarding the clumpy structure of the outflows). The extremely low-density wind material is a consequence of our not including a full IGM into which the winds can propagate; this also causes the winds to cool adiabatically (hence the secondary ‘bump’ of warm/cold gas at extremely low densities). However, it is fairly generic that the cold/warm/hot material dominates the wind at high/intermediate/low densities, respectively. It is especially worth noting that the winds can include some cold gas at densities \( \sim 1–100 \text{ cm}^{-3} \) (this is primarily material still near or within the disc, being accelerated outwards); as it escapes, the gas expands and can easily be heated.\(^8\) In the gas-rich mergers, the contributions to the wind mass from cold/warm/hot phases are comparable, although in the dwarf systems (SMC and Sbc) the very low-density ‘warm’ component was mostly ‘hot’ when originally ejected; in the gas-poor MW-like case, there is relatively little material to ‘entrain’ and torques are able to efficiently force most of the dense gas into a starburst, so the outflow is much more strongly dominated by hot, venting gas.

5 VELOCITY STRUCTURE OF OUTFLOWS

Fig. 6 shows that in all cases the winds have a broad velocity distribution extending to \( > 1000 \text{ km s}^{-1} \), but most of the wind mass is near \( \sim V_c \), with relatively little (\( \lesssim 1% \) of the mass) at large \( v \gg 500 \text{ km s}^{-1} \). Observationally, winds in bright ULIRGs have velocities similar to those here (Heckman et al. 2000; Martin 2005; Rupke, Veilleux & Sanders 2005), but in AGN-dominated, late-stage mergers the wind velocities typically reach much larger values, \( \sim 500–2000 \text{ km s}^{-1} \) (see e.g. Feruglio et al. 2010; Greene et al. 2011; Rupke & Veilleux 2011; Sturm et al. 2011; Greene, Zakamska & Smith 2012).\(^9\) This suggests that wind velocity may be a useful observational discriminant between starburst and AGN driving mechanisms. We find that, without AGN feedback, the distribution of wind velocities below the escape velocity but above the disc circular velocity is quite flat; above this characteristic velocity however, it is exponentially decreasing with increasing \( v_r \).

Fig. 7 shows the geometry of this velocity field on different scales, for a specific system (HIz e) at a given instant (pre-coalescence

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\(^9\) Note that these are the outflows on galactic scales; there are much higher velocity outflows still associated with broad absorption line systems and outflows near the AGN itself (for a review, see Veilleux, Cecil & Bland-Hawthorn 2005), although some of these may even have substantial components at \( \sim \text{kpc} \) scales (Bautista et al. 2010; Dunn et al. 2010).
Figure 6. Top: distribution of gas temperature (weighted by thermal bremsstrahlung emission), $dL_X/d\log T_{\text{gas}}$, at $\approx$200 Myr after the final coalescence in the merger. Different lines in each panel denote gas with different radial velocity (relative to the centre of mass). Emission from more rapidly outflowing wind material is dominated by hotter gas ($T \sim 10^6–10^8$ K). Middle: mass-weighted distribution of gas outflow radial velocities ($dn/dv_r$). We show separately the distribution from three phases: cold ($T < 2000$ K), warm (primarily ionized) ($2000 < T < 4 \times 10^5$ K) and hot/diffuse ($T > 4 \times 10^5$ K) gas. The outflows consist primarily of a mix of warm and hot gas, with some colder material. Warm material typically dominates by mass, in the form of filaments and shells [in Fig. 2; note that the dense ‘cloudlets’ at large radii, while visually prominent, are partly numerical and do not dominate by mass (see footnote 8 in the text)]. Bottom: mass-weighted density distribution for the wind gas, divided into phases as in the middle panel. The ‘warm’ material at very low densities, $\ll 10^{-4} \text{ cm}^{-3}$, is previously ‘hot’ material that has adiabatically cooled as it expands; these low densities arise artificially because we do not include an IGM into which the wind expands.

Figs 8–10 attempt to give an estimate of the observable line-of-sight velocity distribution. In Fig. 8, we show the mass-weighted line-of-sight velocity distribution of all gas for each galaxy, at the snapshot nearest to the peak in the starburst (generally shortly after nuclear coalescence), after projection onto a random axis. We stress that a direct model of e.g. an observed line profile requires properly modelling emission and absorption and involves three-dimensional line transport, which can differ significantly between lines and is outside of the scope of our study here (but see e.g. Cooper et al. 2009). But this gives a rough guide to observed behaviours, especially if we consider different phases separately. In the cold gas especially, we see multiple narrow components with separations comparable to the circular velocity; these reflect unrelaxed merger kinematics. But in the cold/warm gas, and especially in the hot gas, we also see broad wings extending to a few hundred km s$^{-1}$, a direct consequence of the winds. In Fig. 9, we show the same for just one system but spatially resolved across the halo. This makes obvious how the narrow component corresponds to different dense filaments and clumps, but also shows how both the narrow offset and broad winds systematically vary across the galaxy (owing primarily to projection effects). The broad wings have a lower covering factor,
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Figure 7. Image of the gas velocity field. The gas (colour-coded in the style of Fig. 2) is shown for the galaxy in Fig. 1 at the same time, in a face-on (top) and edge-on (bottom) projection, with the (projected in-plane) velocity vectors plotted. The vectors interpolate the gas velocities evenly over the image; their length is linearly proportional to the magnitude of the local velocity with the longest plotted corresponding to \( \approx 500 \mathrm{ km \ s}^{-1} \). The spatial scale of each image is \( \pm 50 \mathrm{ kpc} \) (left), \( \pm 100 \mathrm{ kpc} \) (middle), and \( \pm 200 \mathrm{ kpc} \) (right). On scales near the galaxies, the field is complex and the outflow ‘launching’ region traces the entire disc surface, with significant non-radial components from the disc and merger orbital motion. On much larger scales, the outflow is primarily radial.

Figure 8. Line-of-sight velocity distribution of the galaxies, on linear scale. Specifically, we project each galaxy along a random axis at a time near the peak starburst (just after final coalescence), and take the integrated \( \mathrm{ d}N/\mathrm{d}v_{\mathrm{los}} \) for all gas, and for the gas separated by temperature (as Fig. 6). Disturbed merger kinematics manifest as asymmetry in the ‘core’, the winds are evident in the broad ‘wings’ extending to several hundred \( \mathrm{ km \ s}^{-1} \). We caution that this is not the same as an actual observed line profile (there is no accounting for emission/absorption here), but gives an idea of the line-of-sight kinematics in the relevant gas phases.

but are more obvious out at large radii, as material has escaped to larger scales more quickly. Note the resemblance between the distributions here and those suggested in observed starbursts (e.g. Martin & Bouché 2009; Steidel et al. 2010; Gauthier & Chen 2012).

In Fig. 10, we plot the radial outflow velocity of all gas versus three-dimensional distance from the galaxy centre, at the end of one example simulation (i.e. at a post-starburst time, although the result is qualitatively similar at earlier times). The broad velocity distribution and mix of orientations/directions are obvious at smaller radii, as is the trend towards primarily radial outflow at the largest radii (since this is material which has escaped the galaxy). A Hubble-like flow develops quickly, and fitting a power law to the median \( v_r \) versus \( r \) gives \( v_r \propto r^{0.7-1.0} \). Some of the increase in velocity with distance owes to continuous acceleration, but most of the trend simply arises because the fastest moving material escapes to the largest radii. We also show the velocity in projection, plotting the line-of-sight velocity versus projected distance for all gas. As expected, projection effects greatly broaden the distribution. However, the trend is similar – fitting a power law \( |v_{\mathrm{los}}| \propto R_{\mathrm{proj}}^{0.7-1.0} \) gives a similar scaling.

6 OUTFLOW RATES AND MASS-LOADING EFFICIENCIES

In Figs 11 and 12, we show the wind mass outflow rate during the mergers. Fig. 11 shows it in absolute units. However, the outflow rate is typically quantified in terms of its ratio to the SFR \( M_{\mathrm{wind}}/M_* \), i.e. the wind mass per unit mass of stars formed, so we show this
in Fig. 12. In both cases, we define the ‘wind’ as material with a positive Bernoulli parameter $b = (v^2 + 3 \epsilon^2 - v_{esc}^2)/2$, i.e. material that would escape in the absence of additional forces or cooling. In Fig. 12, we show the wind mass above different absolute radial velocity cuts to highlight the characteristic velocities.\textsuperscript{10}

\textsuperscript{10} Note that the first $\sim 10^8$ yr reflect both out-of-equilibrium initial conditions and contributions from the ‘pre-existing’ stars in the initial conditions to the outflows (not the self-consistently formed stars in the simulation), so should be ignored.

To first order, the wind mass-loading efficiency does not strongly depend on the merger stage. The absolute outflow rate in Fig. 11 during the starburst is very large, $\sim 1$–10 times the SFR for the models here or $\sim 10$–500 $M_\odot$ yr$^{-1}$ in absolute units. But Fig. 12 shows that this is not proportionally much larger than what is seen for the isolated versions of these galaxy models; $M_{\text{wind}}/M_*$ is relatively flat in time. In some cases, it even drops as the merger begins; this is because of the increase in surface densities making the escape of photons and hot gas needed to drive the winds less efficient. In Paper III, we parametrize the dependence of total wind mass loading...
entrained material 'blown out'. It is, in short, below the threshold of
specific SFR is much lower than any other model; the result shown
in the wind mass loading at the first passage and coalescence bursts.
This is because, for that model, the gas fraction is small and so the
gas fraction is large (the low-mass Sbc case), where
SFR or 'feedback strength' needed to blow out more material. But
when the specific SFR is boosted in the merger passages, this allows
it to drive efficient winds. This is not captured in the simple scaling
for wind mass-loading efficiencies proposed for isolated galaxies in
Paper III.

7 EFFECTS OF OUTFLOWS ON SF IN MERGERS

The SF properties of the simulations here are discussed in detail in
Paper IV. However, here we wish to consider how these are affected
by the outflows generated in the merger. In particular, in previous
work on galaxy mergers (as discussed in Section 1) it was not possi-
ble to explicitly resolve wind generation, and instead simulations
used a variety of subgrid approaches designed to model some 'ef-
effective' wind scalings. We wish to examine how the consequences
of these winds differ from those here.

Fig. 13 shows the SFR versus time in a couple of our mergers,
compared to simulations with identical initial conditions run using
a simplified 'subgrid' treatment of stellar winds and the ISM from
Springel & Hernquist (2003a). In that model, rather than resolving
the microstructure of the ISM below ~kpc scales, gas is assigned
an 'effective equation of state' (i.e. effective pressure above a low-
density threshold = 1 cm$^{-3}$ where the medium is assumed to become
multiphase) motivated by the interplay of GMC formation and de-
struction, and turbulent driving and heating via stellar feedback. In
the 'subgrid' treatment, the lack of resolution of SF and feedback
means that SF is assigned statistically to gas at much lower den-
sities, with an efficiency that must be tuned so that the model lies
on the Kennicutt relation. Stellar winds are not resolved, so gas
particles are instead stochastically kicked out of the galaxy at a rate
proportional to the SFR, with a fixed velocity and mass loading;
they are then 'free-streamed' (temporarily decoupled from the hy-
drodynamics) until they escape to a few kpc from the galaxy centre
(this simply guarantees that the assigned mass loading is the actual
wind mass, rather than most of it going into e.g. local turbulence).
Here, we match the mass loading to the mean measured in each
simulation with the full treatment of feedback; the velocity loading
corresponds to a fraction = 0.1 of SN energy coupled, but is dynami-
cally irrelevant because of the free-streaming condition. For simplic-
ity, we compare just the Sbc and MW e models, though the differences are robust across other simulations
(the differences for the f orbits are similar but less pronounced
since the orbit produces a less extreme starburst).

We clearly see that the subgrid wind models 'wipe out' some of
the starbursts at the time of coalescence. This occurs because the
wind prescription blows material away at all densities, as the gas
falls into the centre; it thus effectively suppresses material actually
going into a dense, kpc-scale nucleus in the first place (rather than
blowing out the material after the starburst begins). It also occurs
because material cannot be 'saved' for the starburst (this requires
resolved phase structure), nor can dense portions of inflows 'resist'
the outflow occurring simultaneously. A consequence of this is that
the mergers with certain simplified subgrid wind models – even of
gas-rich discs on favourable orbits – have difficulty in reproducing
ULIRGs and other extremely bright merging systems observed (see
e.g. Cox et al. 2006a; Davé et al. 2010). The effect appears more
severe when gas fractions are large (the low-mass Sbc case), where

\[ \langle \frac{M_{\text{wind}}}{M_e} \rangle \approx 10 \left( \frac{V_e(R)}{100 \text{ km s}^{-1}} \right)^{-(1.0 \pm 0.3)} \left( \frac{\Sigma_{\text{gas}}(R)}{10 \text{ M}_\odot \text{ pc}^{-2}} \right)^{-0.5 \pm 0.15} \]

\[ (1) \]

with a scatter of ~50 per cent in normalization. This appears to
provide a reasonable fit to the values in Fig. 12.

In the MW case, however, there does appear to be a sharp increase
in the wind mass loading at the first passage and coalescence bursts.
This is because, for that model, the gas fraction is small and so the
specific SFR is much lower than any other model; the result shown
in Paper III is that the 'wind' (in the isolated MW case) is mostly
directly venting hot gas from SNe and stellar winds, rather than any
entrained material 'blown out'. It is, in short, below the threshold of

\[ 11 \]

Though we caution that because of the differing implementations, it is
difficult to exactly define 'matched' mass loadings.
Figure 11. Galactic superwind mass outflow rates $\dot{M}_{\text{wind}}$. We compare each disc model (labelled) and both orbits. The mass outflow rate is averaged over $\approx 2 \times 10^7$ yr intervals, about a dynamical time; wind material is defined by a Bernoulli parameter $b > 0$. The absolute outflow rates are highest in the HiZ case (up to $\sim 600 \, M_\odot \, \text{yr}^{-1}$ over these time-scales), but even in the SMC case reach $\sim 10 \, M_\odot \, \text{yr}^{-1}$. The peaks broadly follow the starbursts at first couple passages and final coalescence. There is surprisingly little orbital dependence in the typical outflow rates.

the merger with subgrid winds barely produces an enhancement of the SFR.\footnote{Note that, in Paper IV, we compared the SFRs in the simulations here to those in models with an ‘effective equation of state’ but no stellar wind model. In that case, the starbursts are more pronounced, since there is no wind to ‘wipe out’ the inflow.}

In contrast, in the simulations with resolved feedback, the cold, dense, compact gas being strongly torqued (and hence tightly bound) is difficult to entrain, and so more survives to contribute to the starburst, which then efficiently blows out less bound material recycled from inside clouds and/or being contributed from more diffuse flows at slightly later times. As shown in Paper IV and herein, this simultaneously produces large SFR enhancements (comparable to ‘subgrid’ models with zero wind mass loading) and ULIRG/hyper-LIRG luminosities, while driving winds with large mass-loading factors.

We also see that the post-merger ‘tail’ of SF is significantly different in subgrid wind models. This is because the wind, by design, completely escapes the galaxy; meanwhile with no resolved feedback (merely effective pressure) in the disc, the material which remains is efficiently exhausted by SF. In the simulations from Paper IV with no winds (but still using an effective equation-of-state model), nearly all the gas is efficiently exhausted (as expected). However, in the simulations with resolved feedback, there is a wide range of material in fountains with broad velocity, density and temperature distributions (in addition to the unbound wind); in the best-studied systems, this also appears to be observationally true (Strickland & Heckman 2009). Some of this then continuously rains down at later times on to the post-merger system.

Fig. 14 quantifies this by plotting the distribution of Bernoulli parameters $b$ for the gas, at the time just after peak starburst. There is a long tail towards $b \gg 1$ which is the unbound material, but even at large radial velocities $v_r > 100 \, \text{km s}^{-1}$ and distances $>10 \, \text{kpc}$ from the disc, a non-trivial fraction of the wind material (tens of per cent) is bound ($b < 0$). This will rain down on the disc on a wide range of time-scales corresponding to the broad velocity distribution, from $\sim 100 \, \text{Myr}$ to several Gyr, and re-supplies the ‘tail’ of SF at late times. In contrast to simply concentrating the gas in one place at one time, this makes a complete ‘shutoff’ of SF much more difficult.

8 DISCUSSION

In a series of papers, we have implemented detailed, explicit models for stellar feedback that can follow the formation and destruction of individual GMCs and star clusters: the models include SF only at extremely high densities inside GMCs, and the mass, momentum and energy flux from SNe (Types I and II), stellar winds (both ‘fast’ O-star winds and ‘slow’ AGB winds) and radiation pressure (from UV/optical and multiply scattered IR photons), as well as H II phot ionization heating and molecular cooling. Here, we extend our models of isolated discs from previous papers to include major galaxy mergers. As a first study, we focus on simple, global properties and compare them to those obtained from previous generations of simulations which did not follow these processes explicitly but instead adopted a simplified ‘effective equation of state’ subgrid model of the ISM.
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Figure 12. Average galactic wind mass-loading efficiency ($\equiv M_{\text{wind}}/M_{\text{new}}$, where $M_{\text{wind}} = \int \dot{M}_{\text{wind}}$ and $M_{\text{new}} = \int \dot{M}_*$) for each galaxy model ($f/e$ orbits shown as solid/dotted lines as Fig. 11). As shown in Paper III, the mass loading increases going from high-mass (HiZ, MW) systems to lower mass (Sbc) and dwarf (SMC) galaxies. The mechanisms dominating the outflow also transition from radiation pressure to SNe, respectively. As isolated discs, the HiZ, Sbc, MW, SMC models have $M_{\text{wind}} \sim (1, 3-5, 1-3, 10-20) M_*$. Similar values appear here, with weak time dependence. Although the absolute outflow rates in starbursts in Fig. 11 are very large, they follow from large SFRs; the mass-loading efficiency is more sensitive to global galaxy properties than merger stage. We also consider the mass loading of material with various cuts in the outflow radial velocity $v_r$ (in km s$^{-1}$); the distribution of outflow velocities is very broad (see footnote 10 in the text).

With explicit feedback models, superwinds are generated in all passages with outflow rates from $\sim 10$ to 500 $M_\odot$ yr$^{-1}$. The simulated outflow rates are suggestively similar to observations of starburst winds in many observed ULIRGs and merging galaxies (cf. e.g. Heckman, Armus & Miley 1990; Martin 1999, 2005, 2006; Heckman et al. 2000, Rupke et al. 2005; Grimes et al. 2009; Sato et al. 2009; Coil et al. 2011; Rubin et al. 2011; Gauthier & Chen 2012).

Although the absolute outflow rates can be enormous in the starburst, we find that the mass-loading efficiency – i.e. the outflow rate per unit SFR – is broadly similar for each galaxy model to the isolated version of that system. In other words, outflow efficiencies – on average – appear to depend more strongly on global dynamical properties (escape velocity, effective radius) than on the instantaneous dynamical state of the system. The characteristic mass-loading efficiency scales inversely with the escape velocity of the systems, increasing from about unity in massive systems ($\sim 10^{11} M_\odot$) to $\sim 10-20$ in SMC-mass dwarfs. However, since the absolute SFRs are much larger in massive systems, the absolute outflow rates tend to increase with galaxy mass (for gas-rich systems). We caution that, as for isolated systems in Paper III, there is very large variability in the instantaneous mass-loading efficiency $M_{\text{wind}}/M_*$ – at least an order-of-magnitude scatter.

We make predictions for the distribution of velocities, densities and temperatures/phases of the outflows, which extend those shown in Paper III for isolated discs. The distribution of velocities is broad, as shown for isolated systems in Paper III, but extends characteristically to the escape velocity (a couple times the maximum circular velocity), with a long (but relatively low-mass) tail of material in higher velocity components. This is also similar to observations – typical velocities are a couple to a few hundred km s$^{-1}$ (references above). The winds are characteristically multiphase, with a large fraction of the mass in each of the cold, warm ionized and hot (pressure-supported) phase, and a broad range of densities spanning several orders of magnitude. The cold phases are predominantly accelerated by radiation pressure and become more prominent in the more gas-rich, higher density systems, including the central regions of the merger, while gas heated to high temperatures by SN ejecta is more prominent in low-mass and/or gas-poor systems, and in the more diffuse (volume-filling) outflow.

In contrast to isolated discs, the wind kinematics are (unsurprisingly) complex. The winds do not entirely originate in the nuclear starburst, but over the entire surface of the discs as the merger proceeds; not only do the extended discs contain non-trivial SF (see Paper IV), but the material there (being lower density, less tightly bound, and less strongly torqued) is easier to accelerate into the wind (or entrain in the outflow emerging from the very centre). As such, near the discs the kinematics retain memory of the orbit and disc rotation (as well as more chaotic components from individual super star clusters on sub-kpc scales), as has been mapped in detailed studies of local merging systems (Martin 2006). On larger scales, the outflow becomes primarily radial, but tends towards a unipolar or bipolar structure; however, since the disc orientations are changing during the merger, this leads to multiple overlapping shells/bubbles.
Figure 13. SFR versus time for our simulations Sbc and MW (‘full feedback’; for the remaining simulations, see Paper IV fig. 8). We compare to simulations run with identical initial conditions but a subgrid model for both the ISM phase structure (‘effective equation of state’) and winds (particles ‘kicked out’ of the galaxy at fixed mass loading, matched to the mean value in the corresponding ‘full feedback’ simulation). The subgrid wind model ‘wipes out’ substructure, blowing out gas before it collects in the central kpc and dramatically suppresses the multiphase starbursts. Also, because gas in the winds is completely ejected from the galaxy, the post-merger SFR decays too quickly in the subgrid model. The difference is larger in the Sbc case because the subgrid wind is assigned a larger mass loading (=5, versus =1 for the MW model), but evident in both.

This multiphase nature of the wind and its driving across the disc are critical to the fact that systems can *simultaneously* drive winds with large average mass-loading factors and also avoid ‘wiping out’ all structure inside the disc – including the kpc-scale gas concentrations that power the starburst itself! In contrast, subgrid models which do not resolve the generation of winds but simply insert some mass loading by hand can produce very different results. We show that some implementations of these subgrid models can suppress the merger-induced enhancement of the SFR – which can (when mass loadings are large) make it difficult to form ULIRGs or bright submillimetre galaxies. This may be related to some known difficulties reproducing these rare populations in cosmological simulations (e.g. Davé et al. 2010; Hayward et al. 2011). It is clear that careful treatment of subgrid wind models is necessary if one wishes to properly resolve the dynamics of gas flows and SFR enhancements within galaxies.

It is also important that a significant fraction of the wind material is not unbound, and falls back into the disc over the couple Gyr after the final coalescence starburst, leading to a slow, extended ‘tail’ in the starburst decay. Especially in prograde mergers, this can greatly enhance the magnitude and duration of post-merger SF, relative to the older models which treat the ISM and feedback physics in a ‘subgrid’ manner. This has important implications for ‘quenching’ of SF in massive galaxies. If quenching were possible without the presence of some additional feedback source – say, from an AGN – then the simulations here are the most optimal case for this. They are cosmologically isolated galaxies, so there is zero new accretion; moreover, an equal-mass merger represents the most efficient means to exhaust a large amount of gas quickly via SF, much more so than an isolated disc (see e.g. Hopkins et al. 2008a,b). However, we find that with the presence of stellar feedback, many of our models – including the already gas-poor MW-like system, maintain post-merger SFRs nearly as large as their steady-state pre-merger SFR.
The systems simulated here would take several Gyr to cross the ‘green valley’ and turn red, much longer than the <Gyr quenching time-scale required by observations (see Martin et al. 2007; Snyder et al. 2011). Far from resolving this by gas expulsion, stellar feedback makes the ‘quenching problem’ harder. As shown in Moster et al. (2011), addition of realistic gas haloes around the merging galaxies (even without continuous accretion) only further enhances the post-merger SFR. This is the short-time-scale manifestation of a general problem in cosmological simulations; over a Hubble time, recycled material from galaxy progenitors is re-captured, and leads to large SFRs and excessive stellar masses in high-mass galaxies (Oppenheimer et al. 2010). If gas is to be swept out of galaxies efficiently after a merger or starburst, the models imply that some other form of feedback – perhaps from bright quasars – is necessary. This is also suggested by observations of late-stage mergers, which find that in the AGN-dominated systems at quasar luminosities, outflow masses are enhanced and the outflow velocities reach \( \sim 1000 \text{ km s}^{-1} \), larger than those we find driven by stellar feedback (Tremonti, Moustakas & Diamond-Stanic 2007; Ferruglio et al. 2010; Rupke & Veilleux 2011; Sturm et al. 2011). These high velocities (well above the escape velocity) may provide a unique signature of AGN-driven outflows, since our simulations drive very little mass to such high values. But we caution that the relative timing of AGN and starbursts is uncertain (though the simulations suggest that AGN follow the starburst; see Hopkins 2011), and AGN (owing to their complicated duty cycles) may not still be active when AGN-driven winds are observable.

In a companion paper, we will examine the star clusters formed in these simulations. The mass/luminosity distribution, spatial locations, formation time distribution and physical properties of these clusters represent a powerful constraint on small-scale models of the ISM and SF.

We have also restricted our focus to major mergers. Studies of mergers with varying mass ratios suggest that the qualitative behaviours discussed here should not depend on the mass ratio for ratios to about 3:1 or 4:1, and even at lower mass ratios they can be considered similar but with an ‘efficiency’ of inducing starbursts and violent relaxation that scales approximately linearly with the mass ratio (Hernquist & Mihos 1995; Naab & Burkert 2003; Cox et al. 2008; Younger et al. 2008a). Since the simplest properties of the winds (e.g. their mass loading and characteristic velocities) seem to scale relatively simply between isolated discs and major mergers, we expect that minor mergers will represent an intermediate case.

We note that recent studies comparing cosmological simulations done with GADGET and the new moving mesh code AREPO (Springel 2010) have highlighted discrepancies between grid codes and SPH in some problems related to galaxy formation in a cosmological context (Agertz et al. 2007; Bauer & Springel 2012; Kereš et al. 2012; Sijacki et al. 2012; Torrey et al. 2012; Vogelsberger et al. 2012). However, we have also performed idealized simulations of mergers between individual galaxies and found excellent agreement between GADGET and AREPO for e.g. gas-inflow rates, SF histories and the mass in the ensuing starbursts (Hayward et al., in preparation). Moreover, in Hopkins (2013) we show that many of these discrepancies can be resolved with small modifications to the equations of motion, and test the differences in galaxies with the full feedback models presented here. Although subtle numerical issues can influence quantities like fluid mixing and hence hot gas cooling, we show that the SFRs agree very well and wind masses agree to within a factor of 2, much smaller than the differences if we remove feedback. Finally, the differences in numerical methods are also minimized when the flows of interest are supersonic (as opposed to subsonic), which is very much the case here (Kitsionas et al. 2009; Price & Federrath 2010; Bauer & Springel 2012).

These new models allow us to follow the structure of the gas in the central regions of starburst systems at high resolution. This makes them an ideal laboratory to study feedback physics under extreme conditions in, say, the centre of Arp 220 and other very dense galaxies. We have also, for clarity, neglected AGN feedback in these models, but we expect that it may have a very significant effect on the systems after the final coalescence (e.g. Di Matteo, Springel & Hernquist 2005; Springel, Di Matteo & Hernquist 2005a,b). With high-resolution models that include the phase structure of the ISM, it becomes meaningful to include much more explicit physical models for AGN feedback.

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APPENDIX A: NUMERICAL TESTS OF THE SPH METHOD AND WIND PHASE STRUCTURE

In this appendix, we discuss the robustness of the numerical methods used here – in particular, we wish to study how the small-scale phase structure of the outflows can be affected by details of the methodology.

Our default simulations in this paper use the standard ‘density–entropy’ formulation of the SPH equations of motion in GADGET from Springel & Hernquist (2002). This formulation manifestly conserves momentum, energy, angular momentum and entropy (in the absence of sources/sinks), and has a number of additional advantages, but produces a resolution-scale ‘surface tension’-like error term at contact discontinuities, which has the effect of suppressing the growth of some fluid mixing instabilities, and has been the subject of much discussion in the literature (see Agertz et al. 2007; Read & Hayfield 2012, and references therein).

Since the multiphase winds may well be subject to exactly these instabilities, we have re-run a subset of our simulations using the newer ‘pressure–entropy’ SPH formulation described in Hopkins (2013), which is shown there to give dramatically improved results in situations with fluid mixing around contact discontinuities (e.g. the Kelvin–Helmholtz and Rayleigh–Taylor instabilities) while retaining excellent conservation properties, and includes a number of additional improvements to the treatment of artificial viscosity (see Cullen & Dehnen 2010), SPH smoothing kernel accuracy (Dehnen & Aly 2012) and timestep communication relevant for treating extremely high Mach-number shocks (Saitoh & Makino 2009; Durier & Dalla Vecchia 2012). For extensive numerical tests demonstrating accurate treatment of these instabilities, see Hopkins (2013).

To test whether these subtleties may be strongly influencing our results, we first consider an isolated, star-forming disc (the progenitors in the SMC model mergers), which was analysed in Hopkins (2013). In that paper, we ran otherwise exactly identical simulations (including the identical physical prescriptions to the merger simulations herein), but adopted either the density–entropy ‘standard’ SPH or newer Hopkins (2013) ‘pressure–entropy’ form (in that case, keeping the kernel and all other properties fixed between the simulations). Fig. 15 in that paper compared the morphology of the isolated discs in those simulations. There we showed that the results were very similar; there were some small differences where the pressure–entropy formulation led to increased mixing along phase boundaries owing to the instabilities above, producing less sharp divisions between molecular regions and hot bubbles. In that paper, we also compared the SFR and wind outflow rates as a function of time from the same isolated (SMC) discs. The time-averaged SFR differed only by ~20 per cent. The total wind mass loading was somewhat more strongly altered, and was lower in the pressure–entropy formulation by a factor of ~1.5–2 because the increased mixing adds some cold gas to the hot medium which then substantially increases the hot gas cooling rate. So this suggests that the absolute wind mass loading should be considered uncertain at the factor of ~2 level, in isolated discs.

Here, we extend this to compare a merger of these galaxies, our SMC f model. Fig. A1 shows the morphology of the winds at large radii in the merger (as Fig. 2), for our standard ‘density–entropy’ SPH formulation, and the newer ‘pressure–entropy’ formulation. In the latter case, we now use the fully updated code from Hopkins (2013), with a more accurate artificial viscosity scheme, SPH kernel and timestep limiter. In the newest version of the code, we have also implemented heating from the $z = 0$ UV background as tabulated in Faucher-Giguère et al. (2008), accounting for self-shielding, and we include this as well since it may well alter the phase distribution of the gas at large radii. The resulting differences at large radii are much more visually striking than those in the star-forming disc: the cold clumps or ‘blobs’ at large radii disappear in the new simulation. We stress that the morphology of the smooth gas – both the diffuse volume-filling hot gas and the warm shells/filaments – is nearly identical. And within the star-forming disc, GMCs still form near the merging SMC model mergers, which was analysed in Hopkins (2013). In that paper, we ran otherwise exactly identical simulations (including the identical physical prescriptions to the merger simulations herein), but adopted either the density–entropy ‘standard’ SPH or newer Hopkins (2013) ‘pressure–entropy’ form (in that case, keeping the kernel and all other properties fixed between the simulations). Fig. 15 in that paper compared the morphology of the isolated discs in those simulations. There we showed that the results were very similar; there were some small differences where the pressure–entropy formulation led to increased mixing along phase boundaries owing to the instabilities above, producing less sharp divisions between molecular regions and hot bubbles. In that paper, we also compared the SFR and wind outflow rates as a function of time from the same isolated (SMC) discs. The time-averaged SFR differed only by ~20 per cent. The total wind mass loading was somewhat more strongly altered, and was lower in the pressure–entropy formulation by a factor of ~1.5–2 because the increased mixing adds some cold gas to the hot medium which then substantially increases the hot gas cooling rate. So this suggests that the absolute wind mass loading should be considered uncertain at the factor of ~2 level, in isolated discs.

Figure A1. Morphology of the gas in the merging SMC f model, with colours encoding temperature as in Fig. 2. We compare two projections of the same simulation (at an identical time near coalescence). The ‘density–entropy’ case is the standard formulation of the SPH equations of motion, our ‘default’ model in the paper. The ‘pressure–entropy’ case has been re-run with a new SPH code using the alternative ‘pressure–entropy’ formulation of SPH developed in Hopkins (2013), which resolves some known problems in the ‘standard’ SPH method treating fluid mixing instabilities and contact discontinuities (e.g. the Kelvin–Helmholtz instability). The new code also features an improved SPH smoothing kernel, artificial viscosity scheme, and includes UV background heating and self-shielding. The morphology of the hot gas shells/bubbles, warm outflowing filaments/shells at ~10–100 kpc and tidal tails is very similar. However, the previously cool gas at large radii (~10 kpc) is now photoheated to ‘warm’ temperatures (in e.g. the tidal tails). The biggest difference is that the small, cold clumps at the largest radii (which were never self-gravitating and appeared to form in the outflow in the density–entropy models) do not appear in the new code. They are a numerical artefact of the ‘density–entropy’ equation of motion.
These distinctions are more evident in the distribution of gas phases. In Fig. A2, we repeat Fig. 4 and examine the density distribution of gas in the winds, ionized disc and star-forming disc, as well as the specific phase breakdown within the star-forming disc. We compare both the isolated and merging SMC models with both density–entropy and pressure–entropy SPH. First, we emphasize that all of our qualitative conclusions appear robust. There are some quantitative changes, but most of these are in the tails of the density distributions, relevant at the sub-per cent level. Within the star-forming disc, we see that the phase distributions are very similar in both implementations of SPH. Furthermore, including the ionizing background self-consistently has very little effect, except to truncate the cold gas density distribution at just about the density where our previous simple post-processing estimate led us to truncate the distributions. The predicted properties within the disc appear very robust.

In Fig. A3, we extend this comparison to the velocity and density distributions of the wind material (as in Fig. 6). Here, we see larger differences, as expected from the previous figures. In the pressure–entropy SPH, enhanced mixing of cold and hot phases decreases the relative importance of both in the wind, and enhances the relative importance of the warm-phase gas. The presence of an ionizing background also contributes to this. However, in each case we stress that warm-phase gas already dominated the outflow, so this conclusion is robust. The velocity distributions are altered, but only at a modest level – there is still a broad velocity distribution in all phases (in fact, in the models here at the specific time analysed, there may be somewhat more cold material at very large velocities, even though there is less overall in the outflow).

We have specifically chosen to focus on the SMC case because its outflow, being predominantly ‘hot-phase’ gas (but featuring some cold blobs in the density–entropy runs), is most likely to be strongly affected by the details of the numerical method and fluid mixing. We have, however, also re-run lower resolution versions of the HiZ and MW e mergers with both the density–entropy and pressure–entropy formulations of SPH (and have experimented with a wide range of artificial viscosity and smoothing kernel implementations, as well as ionizing background strengths, in the isolated disc progenitors of each). In all these cases, we find that the sense of the difference between SPH formulations is identical to that described above – however, the quantitative magnitude of the difference is smaller in each case (see Fig. A4). The total wind mass loading, for example, is only lower by ∼20 per cent in the MW run, and actually appears to be slightly higher in the HiZ case.

To summarize, the qualitative conclusions and results presented in the main text all appear robust to the details of the numerical method,
Phase structure, velocity and density distributions of the winds of the same simulations as in Fig. A2, in the style of Fig. 6. Top: mass-weighted distribution of gas outflow radial velocities, for all gas and divided into cold/warm/hot phases. Bottom: mass-weighted density distribution of material in the wind, divided by phases. Again we compare the isolated SMC model and SMC \textit{f} merger, at the same instant in time, but with either our default 'density–entropy' SPH or the revised 'pressure–entropy' SPH. The resulting differences in the winds are larger than in the star-forming discs in Fig. A2. However, they are still qualitatively similar. The temperature and density distributions have similar peaks and widths, but differ in their tails. As expected from the morphologies in Fig. A1, the cold ‘blobs’ at large radii are more efficiently mixed with the warm outflow in the pressure–entropy formulation, leading to a smaller cold gas contribution in the wind (but this is not dominant, in any case). In the merger simulation, this mixing also enhances the cooling of the hot gas, so it is reduced as well (making the warm gas component even more dominant). In the merger, the total outflow mass at this stage is systematically lower in the pressure–entropy formulation by about \(\sim 40\) per cent.

**Figure A4.** Wind thermal + metal line emission morphology, as Fig. 3, but for the SMC \textit{f} merger re-run with the revised ‘pressure–entropy’ formulation of SPH (bottom), as well as a HiZ \textit{e} merger run with the pressure–entropy SPH but lower resolution (10 times lower particle number). The large-scale wind behaviour – at least in these simulations which do not include a cosmological IGM – is not strongly sensitive to the numerical method (modulo the small clumps in Fig. A1).

except for the presence of cold ‘blobs’ which form in the outflow. These features are likely driven by the same numerical artefacts that have already been identified as causing the breakup of inflows in cosmological simulations into similar ‘clumpy’ morphologies (see Kereš et al. 2012; Nelson et al. 2013). We stress, however, that these do not dominate the outflows by mass. Moreover, they do not appear until the outflow has essentially escaped the disc. At this point, as we have emphasized in the text, the detailed phase structure predicted should not be taken too seriously, since there is no IGM into which the winds expand. However, this should strongly caution against overinterpretation of the detailed phase distribution in cosmological simulations with outflows (many of which show similar features).

Quantitatively, differences in the numerical method and ionizing background can lead to systematic changes in our predictions for basic wind properties (mass-loading factors, total mass in different phases, maximum velocities) at the factor of \(\sim 2\) level. This is significant. As shown in Paper III, similar uncertainties can arise owing to the manner in which stellar feedback physics is implemented. And this is also comparable to genuine physical uncertainties, for example, the strength of feedback can vary at this level owing to plausible variation in the stellar IMF, or the presence of an equipartition magnetic field and/or cosmic rays (see e.g. Pakmor & Springel 2012; Ullig et al. 2012, and references therein). So we strongly emphasize that considerably more sophisticated simulations are needed (along with improved observational constraints) before any ‘precision’ predictions with accuracy much better than a factor of \(\sim 2\) can be made.