Simulations of the grand design galaxy M51: a case study for analysing tidally induced spiral structure

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ABSTRACT
We present hydrodynamical models of the grand design spiral M51 (NGC 5194), and its interaction with its companion NGC 5195. Despite the simplicity of our models, our simulations capture the present-day spiral structure of M51 remarkably well, and even reproduce details such as a kink along one spiral arm, and spiral arm bifurcations. We investigate the offset between the stellar and gaseous spiral arms, and find at most times (including the present day) there is no offset between the stars and gas within our error bars. We also compare our simulations with recent observational analysis of M51. We compute the pattern speed versus radius, and similar to observations, find no single global pattern speed. We also show that the spiral arms cannot be fitted well by logarithmic spirals. We interpret these findings as evidence that M51 does not exhibit a quasi-steady density wave, as would be predicted by density wave theory. The internal structure of M51 derives from the complicated and dynamical interaction with its companion, resulting in spiral arms showing considerable structure in the form of short-lived kinks and bifurcations. Rather than trying to model such galaxies in terms of global spiral modes with fixed pattern speeds, it is more realistic to start from a picture in which the spiral arms, while not being simple material arms, are the result of tidally induced kinematic density ‘waves’ or density patterns, which wind up slowly over time.

Key words: hydrodynamics – ISM: clouds – galaxies: ISM – galaxies: kinematics and dynamics – galaxies: spiral – galaxies: structure.

1 INTRODUCTION
Nearby galaxies such as M51 provide an ideal basis to examine molecular cloud and star formation, both observationally and theoretically. Whilst the last decade has seen a huge advance in high-resolution hydrodynamic simulations of galaxies (e.g. Wada & Norman 1999; de Avillez & Breitschwerdt 2005; Shetty & Ostriker 2006; Dobbs 2008; Agertz et al. 2009; Tasker & Tan 2009), such calculations are rarely designed to model specific galaxies, e.g. M33, M81, M51 where we are now obtaining detailed CO, Hα and with Herschel, far-infrared observations (e.g. Blitz et al. 2007; Tamburro et al. 2008; Koda et al. 2009). However, several groups have successfully computed orbits of nearby interacting galaxies, including M51 (Salo & Laurikainen 2000a; Theis & Spinneker 2003) and M81 (Yun 1999) using N-body codes. We take the results from one such calculation (Theis & Spinneker 2003) as the basis for modelling the gas dynamics of M51.

1.1 Spiral structure
Spiral galaxies exhibit a variety of morphologies, from flocculent to grand design. Their structure and dynamics are thought to depend on whether the spiral arms are due to small-scale gravitational instabilities in the stars and/or gas, or larger-scale perturbations caused by global density waves, tidal interactions or bars (e.g. Toomre 1977; Lin & Bertin 1985; Elmegreen 1991b, 1995).

Flocculent galaxies are thought to occur when local gravitational instabilities in the gas lead to multiple short arm segments (Elmegreen 1991a, 1995; Bottema 2003; Li, Mac Low & Klessen 2005). When instabilities are present in both the gas and stars, longer spiral arms may develop (e.g. Sellwood & Carlberg 1984; Elmegreen & Thomasson 1993).

In addition to flocculent spirals, grand design galaxies, predominantly with a symmetric two or four armed spiral pattern, constitute around 50 per cent of spiral galaxies (Elmegreen 1982). Traditionally, ‘density wave theory’ has been used to provide an explanation of the spiral patterns in these galaxies, where the stars and gas are assumed to exhibit quasi-stationary standing wave patterns (Lin & Shu 1964). The spiral arms occur where stars are aligned at
particular points of their orbits (Toomre 1977). For both types of spiral, swing amplification may be important either by increasing the amplitude of local perturbations (Julian & Toomre 1966; Toomre 1981; Sellwood & Carlbarg 1984), or by providing a feedback mechanism to maintain wave packets propagating through the disc (Mark 1976; Goldreich & Tremaine 1978; Toomre 1981).

However, an alternative picture is that the grand design spiral structure may be caused predominantly by tides, driven by internal bars or by interactions with other galaxies (Chamberlin 1901; Toomre & Toomre 1972; Tully 1974; Oh et al. 2008). In fact, Kormendy & Norman (1979) proposed that, unless their rotation curves have special properties, all non-barred grand design galaxies must be the result of interactions with nearby galaxies. This view is strengthened by the simulations by Bottema (2003).

The first comprehensive investigation of the degree to which specific grand design spirals could be modelled by tidal interactions was presented by Toomre & Toomre (1972). However, the limitations of the simple analysis of Toomre & Toomre (1972) were such that the tidal features could not propagate radially and so could be induced only in the outer parts of galaxies. Later calculations by Hernquist (1990) of tidal interactions indicated that with higher resolution, and when including a fully consistent gravitational model, more realistic rotation curves and self-gravity of the stars, the spiral structure extends to much smaller radii and is longer lived. Hernquist (1990) found that the tidally induced waves are amplified by the swing amplification mechanism, as predicted by Toomre (1981). Furthermore, the spiral structure is more easily seen and so prolonged when gas is present (Sundelius et al. 1987; Bertin et al. 1989; Chakrabarti 2008). Nevertheless, the tidal encounter could produce the stimulus for a strong density wave perturbation, as originally hypothesized by Toomre & Toomre (1972), and discussed in more detail for M51 by Tully (1974) and Elmegreen, Seiden & Elmegreen (1989).

1.2 Molecular clouds and spurs

For flocculent galaxies, the formation of molecular clouds is most likely intrinsically linked to the formation of spiral structure—gravitational instabilities in the gas lead to both the spiral arms and molecular clouds (Elmegreen 1995). Recently, computer simulations have become capable of modelling the hydrodynamics of such galaxies. Several simulations show the formation of giant molecular clouds in this manner (Wada & Norman 1999; Wada, Meurer & Norman 2002; Li, Mac Low & Klessen 2005; Tasker & Bryan 2006; Robertson & Kravtsov 2008), although collisions between clouds may also contribute (Tasker & Tan 2009). For grand design spirals, giant molecular clouds (GMCs) basically form in the same way, but long-lived spiral perturbations force the gas into the spiral arms periodically, and for longer. Consequently, the growth of instabilities are more confined to, and more dependent on the conditions in the spiral arm, e.g. density, degree of shear. Furthermore, collisional formation of molecular clouds can play a much more important role as the mean free path between collisions decreases (Dobbs 2008).

In addition to molecular cloud complexes along the arms, interarm spurs are clearly visible in many spiral galaxies (Elmegreen 1980; La Vigne, Vogel & Ostriker 2006) and are particularly distinguishable in M51 (Corder et al. 2008). One possibility is that the interarm spurs correspond to features in the underlying stellar distribution (Julian & Toomre 1966; Elmegreen 1980; Byrd, Smith & Miller 1984) and are thus due to gravitational instabilities in the stars. More recent simulations, which assume a static potential, have also shown the formation of spurs purely from the gaseous component of the disc. In this case, GMCs form in the spiral arms [e.g. by agglomeration (Dobbs & Bonnell 2006; Dobbs 2008)] or gravitational instabilities in the gas (Balbus 1988; Kim & Ostriker 2002; Shetty & Ostriker 2006; Dobbs 2008) and are then sheared into spurs as they leave the arms. In the presence of some underlying driving frequency (a global pattern speed), longer gaseous branches may also develop at certain radii due to resonances in the disc (Patsis, Grosbol & Hiotelis 1997; Chakrabarti, Laughlin & Shu 2003; Yáñez et al. 2008). In addition, spurs may be associated with stochastic star formation (Elmegreen 1980; Feitzinger & Schwendtfeiger 1982), but simulations by Shetty & Ostriker (2008) indicate that the stellar feedback tends to disrupt large spurs in the disc.

1.3 Previous models of M51

M51, in particular, is considered the hallmark for grand design galaxies and as such is a prime candidate for the application of density wave theory. However, there are clear indications of a departure from standard density wave theory. Shetty et al. (2007) show huge variations in the velocities of gas in the disc, apparently showing large net radial mass fluxes at some radii, suggesting that the spiral structure of the galaxy is not in a steady state. Furthermore, Meidt et al. (2008) find multiple pattern speeds in M51 (or a radial dependence of pattern speed), indicative that the pattern is both radially and time dependent.

There have been numerous numerical models of M51, (e.g. Toomre & Toomre 1972; Hernquist 1990), but the most thorough are by Salo & Laurikainen (2000a,b). Salo & Laurikainen (2000a) use a least squares technique to find the orbits of the galaxy–galaxy interaction which produce the observed structure. They show that a multiple, rather than single, encounter can produce velocities in the H1 tail in agreement with observations. They also indicate that tidal perturbations overwhelm any pre-existing spiral structure. Salo & Laurikainen (2000b) perform higher resolution simulations, though only with a stellar disc, to investigate inner spiral structure. Similar to Toomre (1969), they propose that the inner spirals are a consequence of tidal waves propagating to the centre of the disc.

In order to analyse the extended parameter space, Theis & Spinneker (2003) instead employ a genetic algorithm to determine the orbit of M51 and NGC 5195. Based on a much larger number of simulations, they corroborate the results of Salo & Laurikainen (2000a) i.e. they find the orbit involves multiple encounters. Both Salo & Laurikainen (2000a) and Theis & Spinneker (2003) require that NGC 5195 lies on a bound orbit to match the spatial and velocity structure of M51.

1.4 The current paper

So far, simulations of grand design galaxies have largely implicitly assumed density wave theory, invoking a global mode with a fixed pattern speed by applying a steady rotating spiral potential (Kim & Ostriker 2002; Dobbs, Bonnell & Pringle 2006; Dobbs 2008). However, if grand design galaxies arise from interactions or bars, it is unclear whether the density wave scenario invoked by Lin & Shu (1964) is appropriate in many galaxies. Thus, it is important to study the gas dynamics and formation of molecular clouds in the context of realistically induced spiral perturbations. For the case of a bar-driven grand design spiral, the spiral is believed to be long-lasting, thus the idea of a spiral structure with fixed pattern speed may well be applicable. This is less likely to be true for interacting
galaxies, where there is a dynamical interaction and a constantly changing spiral structure.

In this paper, we study the dynamics in an interacting system, using orbital data for M51 provided by Theis & Spinneker (2003). Whilst Salo & Laurikainen (2000b) mainly concentrated on the stellar structure and dynamics, we focus on the gas. Salo & Laurikainen (2000a) do include gas in lower resolution simulations, though they use a sticky particle method to evolve the gas particles. We instead use a Lagrangian hydrodynamics code smoothed particle hydrodynamics (SPH) to model a dynamic halo, disc (which contains gas and stars) and bulge. We describe the evolution of the spiral arms, the generation of substructure and the velocities in the gas. We consider whether the evolution of the disc is significantly different from the previous simulations which assumed a static potential and therefore a rigidly rotating density wave.

2 COMPUTATIONAL DETAILS

We model M51 and its interaction with NGC 5195 using SPH, a Lagrangian fluids code. The code is based on an original version by Benz (Benz et al. 1990), but has since been subject to significant modifications, including individual time steps and sink particles (Bate 1995; Bate, Bonnell & Price 1995). More recently magnetic fields have been included (Price & Monaghan 2005; Price & Bate 2007), although these are not used in the current paper.

Unlike GADGET (Springel, Yoshida & White 2001; Springel 2005), which has previously been applied to simulations of interacting galaxies (e.g. Cox et al. 2006; Hachym et al. 2007), our code has predominantly been used for simulations of star formation (e.g. Bate, Bonnell & Bromm 2003; Price & Bate 2008; Bate 2009a,b). Even for calculations of a galactic disc (Dobbs 2008; Dobbs & Bonnell 2008; Dobbs et al. 2008), we restricted our models to the gaseous component of the disc. For the simulations in this paper, we model the stellar disc, bulge and halo, so have therefore adapted the code to include two types of particle, gaseous and stellar.

All particles have variable smoothing lengths, the smoothing length and density solved iteratively according to

$$h = v \left( \frac{m}{\rho} \right)^{1/3}$$

(Price & Monaghan 2007). Here, $\rho$ is the density, $m$ the mass of the particle and $v$ is a dimensionless parameter set to 1.2 in order that each particle has $\sim 60$ neighbours. We calculate smoothing lengths for the gas and star particles separately. For both types of particle, $h$ sets the gravitational softening length, and, for gaseous particles, it is also the SPH smoothing length. Only gas particles are subject to pressure and viscous forces. Artificial viscosity is included to treat shocks, using the standard parameters, $\alpha = 1$ and $\beta = 2$ (Monaghan & Lattanzio 1985).

2.1 The orbit of M51 and NGC 5195

In order to reproduce spiral structure similar to that observed in M51, we model a galaxy representing M51 and its companion galaxy NGC 5195. We assign the initial positions and velocities of the two galaxies according to the results from N-body calculations by Theis & Spinneker (2003). Theis & Spinneker (2003) used MINGA, a restricted N-body code combined with a genetic algorithm code, to determine the orbit of M51 and NGC 5195. In their calculations, the interacting galaxy NGC 5195 is represented by a single point mass, which has one third the mass of M51. The test particles otherwise comprise the disc and bulge of M51 – the halo is represented by a potential. They generated spatial and velocity maps from the outcome of each N-body calculation to compare with observed maps of H I. The genetic algorithm code is used to constrain the parameters of the orbit, and find the best fit to the observed data. The best-fitting model corresponds to a highly elliptical orbit, with two passages of NGC 5195 through the plane of the disc of M51. This model provided the initial velocities and positions for the SPH calculations at a time of $\sim 300$ Myr prior to their current position. At this point in the N-body model, the two galaxies are separated by approximately 24 kpc. The resulting orbit of the two galaxies in the SPH calculations is shown in Fig. 1. The initial positions and velocities of the two galaxies are listed in Table 1.

2.1.1 Dynamical friction

A difference between the simulations presented here and those produced using the MINGA code is that we use a live halo, whereas Theis & Spinneker (2003) use a potential. Consequently, the orbit of the SPH calculations begins to deviate from that derived from the MINGA calculations with time. Petsch & Theis (2008) have since implemented dynamical friction into an improved MINGA code, which takes into account the effect of the companion on the halo. They
also reran the calculations of Theis & Spinneker (2003) using dynamical friction. Unfortunately, they have not yet calculated a new orbit for M51, which includes the effects of dynamical friction.

We did however run calculations of the interaction without gas, to compare with unpublished purely stellar dynamical calculations of Harfst & Theis (private communication). Although Harfst & Theis modelled NGC 5195 as well as M51 (whilst here we adopt a point mass for NGC 5195), we found that after 300 Myr, the difference in the position of the companion, and the structure of the disc was negligible for the N-body and SPH codes. After 500 Myr, the structure of M51 was still the same, although the companion galaxy had shifted about 25° further in its orbit for the SPH code.

2.2 Initial setup of M51 and NGC 5195

We determined the initial distribution of particles in our model of M51 by using the MKKD95 program (Kuijken & Dubinski 1995). This is a publicly available program from the NEMO stellar dynamical software package (Teuben 1995). In the MKKD95 program, we set psi 0 = −7.65 and RA = 0.142 (which determine the size of the halo), md = 1.36 (the mass of the disc), router = 3 (the radius where the disc begins truncate) and drtrunc = 0.25 (the distance over which the disc truncates). The remaining parameters (including those for the bulge) were set as the defaults. We selected these parameters to produce a mass and maximum radial extent for each component similar to those of Theis & Spinneker (2003), although we adopted a slightly less extended halo based on the rotation curve shown in Sofue et al. (1999). However, although the radius and mass chosen for the halo were based on the observed rotation curve, our rotation curve was not as flat as Sofue et al. (1999), peaking at around 275 rather than 250 km s⁻¹. Furthermore, the maximum velocity increases slightly during the interaction. Thus, in retrospect, we ideally would have needed to start with a more extended halo. The main difference this makes to our simulation is that the pattern has rotated further and is therefore slightly out of phase compared to the observed structure of M51 (see Sections 4.1 and 4.2).

The properties of our model of M51 are listed in Table 2, as well as the number of particles in each component. We chose to place the most resolution in the disc (and in particular the gas). Thus, we used one million particles for the disc, 6 × 10⁴ for the halo and 4 × 10⁴ for the bulge, giving a total of 1.1 million. We then assigned SPH particles the velocities, positions and masses outputted from the MKKD95 program.

We work in a Cartesian coordinate system in which the x- and y-axes lie in the plane of the sky, and the z-axis lies towards us along the line of sight. In order to end up with the observed orientation of M51, we start with our model galaxy in the plane of the sky and then perform two rotations, first one of 20° clockwise about the y-axis, and then one 10° counterclockwise about the x-axis. Before adding the perturbing galaxy, we first ran a simulation with stars only, to ensure that the galaxy had a stable configuration.

Lastly, we placed the two galaxies at the relative positions, and with the respective velocities to reproduce their orbit, as determined by Theis & Spinneker (2003). The initial positions and velocities (with respect to our Cartesian grid) of the two galaxies are those shown in Table 1. Similar to Theis & Spinneker (2003), we model the interaction by designating a single particle as the companion galaxy NGC 5195, which has a third of the mass of M51. The softening of the point mass is treated in the same way as the other particles in the simulation. Salo & Laurikainen (2000b) similarly only assigned one particle to NGC 5195, although their first calculations modelled the companion galaxy consistently (Salo & Laurikainen 2000a).

2.2.1 The gaseous component of the disc

We performed three calculations with different conditions for the gaseous component of the disc. In all cases, we set 900 000 random particles in the disc as gas particles – thus leaving 100 000 stellar particles in the disc. In model A, this implied a mass resolution of 180 M⊙ per particle for the gas and 2.4 × 10⁴ M⊙ per particle for the stellar disc. The average smoothing length for the gas particles is 100 pc. We did not change the positions of the gas particles, rather we assumed they would settle in equilibrium in the direction perpendicular to the disc (see Section 3). We then set masses and temperatures for the gas particles, as shown in Table 3. We chose the gas mass to be 0.1, 1 or 10 per cent of the disc mass, and the temperature as either 100 or 10⁴ K. For these calculations, we take a simple approach and assume the gas to be isothermal. The cases where the gas mass is 0.1 or 1 per cent are unrealistically low for a disc galaxy. However, such a low mass largely prevents gravitational collapse in the gas. Gravitational collapse slows down the calculations, and requires the inclusion of sink particles. Furthermore, in order to carry out a global comparison of the gas distribution between models and observations, we

| Table 1. The initial positions and velocities for M51 and NGC 5195 are listed. |
|---------------------------------|---------|---------|---------|
| M51 | NGC 5195 |
| Initial position (kpc) | x | 4.91 | –17 |
| y | 1.89 | –6.55 |
| z | 0.95 | –3.30 |
| Initial velocity (km s⁻¹) | vₓ | –1.46 | 5.86 |
| vᵧ | 0.68 | –2.44 |
| vզ | –3.26 | 15.6 |

Note. These are extracted from the N-body calculations performed by Theis & Spinneker (2003).

| Table 2. The mass, radial extent and number of particles is listed for each component of the M51 galaxy (the radial extent is the distance to the edge of each component, although all fall off with radius). |
|--------------------------------|---------|---------|---------|
| Component | Mass (M⊙) | Radial extent (kpc) | No. particles |
| M51: Disc | 5.9 × 10⁹ | 15 | 10⁶ |
| M51: Halo | 1.45 × 10¹¹ | 20 | 6 × 10⁴ |
| M51: Bulge | 5.25 × 10⁹ | 4.8 | 4 × 10⁴ |
| NGC 5195 | 7.07 × 10¹⁰ | – | 1 |

Note. The companion galaxy NGC 5195 is represented by a single point mass in the simulation, thus has no physical radius.

| Table 3. The properties of the gas component are listed for the three models presented in this paper. |
|--------------------------------|---------|---------|---------|
| Model | Gas mass (per cent of disc) | Temperature (K) | min (Q₉) |
| A | 1 | 10⁴ | 30 |
| B | 10 | 10⁴ | 3 |
| C | 0.1 | 100 | 30 |

Note. The final column is the minimum value of the Toomre stability parameter for the gas (see Section 2.2.2 and Fig. 2).
are mainly interested in the structure induced in the gas in response to the interaction, as opposed to the instabilities in the gas. For the warm \(10^4\) K gas though, which is less susceptible to gravitational instabilities, we also ran a model where 10 per cent of the disc is gas (by mass).

We initially ran a calculation with a temperature of 100 K, setting 1 per cent of the disc as gas. However, this gave rise to widespread self-gravitational collapse throughout the disc. For this reason, we restarted the calculation but taking 0.1 per cent of the mass of the disc to be gas, which was more stable. In addition to running models with an interaction, we also ran a calculation for a galaxy in isolation. For this, we used our fiducial mode (A) with 1 per cent warm gas.

2.2.2 Stability of the disc

To clarify the gravitational stability of the disc, we computed the Toomre stability parameter for the gas \(Q_g\) and stars \(Q_s\). We took \(Q_g = c_s \kappa / \pi G \Sigma\) and \(Q_s = \sigma_s \kappa / 3.36G \Sigma\) where \(c_s\) is the sound speed, \(\kappa\) is the epicyclic frequency, \(\Sigma\) the surface density and \(\sigma_s\) the radial velocity dispersion (Toomre 1964; Goldreich & Lynden-Bell 1965; Binney & Tremaine 1987). A detailed analysis for the Toomre criterion in a two-fluid system is described in Jog & Solomon (1984) and (Romeo 1992), but we adopt the limiting case where one component is stable for our simple analysis here. We show \(Q_g\) and \(Q_s\) versus radius for the least stable case (model B) in Fig. 2. We also state the minimum value of \(Q_g\) in Table 3. As \(Q_g\) is \(\approx 1\) at larger radii, the stars are unstable to perturbations, and as we show in Section 3.1.1, multiple spiral arms develop even in the absence of a tidal interaction. For the model where 10 per cent of the disc is gas, \(Q_g\) is as low as 3, hence the gas is only marginally stable. This is the least stable case – \(Q_g\) is a factor of 10 higher in models A and C.

2.2.3 Sink particles

Even with low surface densities, we found it necessary for computational reasons to allow the formation of sink particles. Sink particles replaced regions with gas densities exceeding \(10^{-12} \text{ g cm}^{-3}\), with...
Figure 4. Column density plots show the time evolution of the simulated interaction of M51 and NGC 5195, at times of 60, 120, 180, 240, 300 (corresponding approximately to the present day) and 371 Myr. These plots only show the gas, which represents 1 per cent of the disc by mass, and has a temperature of $10^4$ K (model A). We model a galaxy representing M51, whilst the galaxy NGC 5195 (a point mass) is indicated by the white spot. Sink particles are otherwise omitted from the figures (see text). The orbit of the companion galaxy is also shown on the panels (the dashed section indicates that the companion is behind the M51 galaxy). The galaxy undergoes a transition from a flocculent spiral to a grand design spiral during the course of the interaction. At the last time frame (371 Myr), the two galaxies are in the process of merging. Note, both the spatial and density scales differ in the lower three plots.

4.1 Structure of the disc

We show the evolution of the gas disc of model A (with 1 per cent warm gas) in Fig. 4, where the interacting galaxy NGC 5195 is visible as a white dot. After 60 Myr (first panel), the interaction is not far advanced, and the structure resembles the flocculent spiral structure seen in the isolated case (Fig. 3). By 120 Myr (second panel), we start to see a two-armed spiral pattern developed at larger radii ($R > 5$ kpc). At later times, the two-armed structure extends to much smaller ($R \sim 2$ kpc) radii. The spiral pattern evidently changes with time, but it evolves more slowly between 240 and 300 Myr. During the simulation, the companion galaxy becomes increasingly bound to the M51 galaxy, and at the latest time (370 Myr), the two galaxies are beginning to merge.

The time of 300 Myr corresponds approximately with the present day in Theis & Spinneker (2003). The orbit in this simulation deviates from the one obtained by Theis & Spinneker (2003) because our active halo permits dynamical friction and therefore the model does not exactly reproduce the current positions of M51 and NGC 5195. Nevertheless, the tightly wound spiral arms and overall morphology strongly resemble that of M51, as we will discuss in Section 4.1.1.

Although not shown in Fig. 4, to avoid confusion with the companion galaxy, the gas disc also contains sink particles. These have been inserted at regions which acquire sufficiently high densities that would otherwise halt the calculation. However, for model A, the disc is still relatively stable and only five such particles form over the course of the calculation.

Interestingly, there appears to be substructure in the gas at all stages of the interaction. Initially, the substructure is flocculent, with many shorter segments of spiral arms, due to gravitational instabilities primarily affecting the gas (Toomre 1964). By 180 Myr (top right-hand panel), the galaxy contains a dominant two-armed spiral pattern. Some remaining flocculent structure is seen towards the top right of the panel ($x = 5$ kpc, $y = 5$ kpc), which has not yet passed through the tidal arms. However, there are also bifurcations of the spiral arms, spurs and material shearing away from the spiral arms, which we discuss further in later parts of the paper.

4.1.1 Detailed analysis of structure and comparison with M51

In Fig. 5, we show a snapshot from our simulation, at 300 Myr roughly corresponding to the present day, accompanied by an Hubble Space Telescope (HST) image of M51. The figures show excellent agreement between the simulations and observations, in particular, the overall shapes of the arms, and their pitch angles.

We note several specific features seen in the simulation, and M51, which are labelled on Fig. 5. First, there is a clear kink in the spiral arm (marked A) in M51, and remarkably, the same feature appears in our model. The kink is slightly further anticlockwise compared to the actual M51, suggesting our model has evolved slightly too far, presumably because the density structure, and hence the rotation curve we have assumed for M51 is not quite right. This kink appears to arise where the inner spiral arm, induced from the previous crossing of the companion, meets a new spiral arm induced by the current passage of NGC 5195. The feature marked B indicates a second spiral arm breaking away from the main arm. This occurs in both model and the actual M51, although again in our model the arm has rotated further round the galaxy. We also see a large degree...
Simulations of tidally induced structure in M51

Figure 5. The top panel is a column density plot from our simulation with 1 per cent warm gas after 300 Myr, whilst the lower panel is a HST image of M51 produced by NASA, ESA, S. Beckwith (STScI) and The Hubble Heritage Team (STScI/AURA). The spiral structure e.g. shape and pitch angle of the spiral arms appears very similar to the actual M51. In addition, we mark on several features (A, a kink in the spiral arm; B, a branch; C, interarm gas; D, a stream of gas extending from the companion) which appear in both the simulation and the observations.

of gas between the spiral arms, in particular, indicated at C, and again this is typical for much of M51.1

A feature which is not seen in the Hubble image of M51, but is present in our model, is a large stream of gas above the uppermost spiral arm (i.e. above C). Interestingly though, we do see gas in front of the companion galaxy (marked D). Possibly, this gas extends further, and would be visible in H\textsubscript{I} (see Fig. 6), or alternatively the gas disc in our model is initially too extended.

In Fig. 6, we show a much larger scale image from our simulation at the same time of 300 Myr, and below an H\textsubscript{I} image from Rots et al. (1990). We capture the H\textsubscript{I} tail of M51 very well. The width of the tail increases up to the corner of the tail, before diminishing. There is also gas far round the tail, i.e. at negative x values in our coordinates, which is apparent in the H\textsubscript{I} image. The entirety of the gas tail has a stellar counterpart. This is as expected since we base our models on the calculations of Theis & Spinneker (2003), who compared the stellar distribution of their results with Rots et al. (1990).

The gas feature at (0,20) kpc in our coordinates is not seen in the observations. We find that this gas has been slung out of M51 by a close passage with the companion. Possibly, there is gas in this region which is not detected. Alternatively, if we properly modelled the companion, rather than using a point mass, the gas may collide with gas internal to the companion and experience less acceleration, or even become accreted by the companion.

From Fig. 5, our simulated galaxy appears slightly stretched in the y direction compared to the actual M51. Although we use the observed position and inclination angles of M51 in our initial conditions, these change over the course of the simulation, and the galaxy becomes less tilted on the plane of the sky. Thus, at 300 Myr, the galaxy appears more face-on than M51. This could suggest that we would need to start with a slightly different orientation to that currently observed for M51, or again reflect a simplification of our model (e.g. representing NGC 5195 by a point mass).

We show the detailed evolution of the disc from 280 to 320 Myr in Fig. 7. The structure of the disc, and the spiral arms, are evidently changing over time-scales of < 10 Myr. Interestingly, we see that the present apparent position of NGC 5195 at the end of one of the spiral arms is merely a coincidence – 10 Myr earlier the companion

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1At 180 Myr (Fig. 4), there is also a stream of gas shearing away from the spiral arm. Thus, the spiral arm appears to bifurcate moving radially inwards along the spiral arm [at coordinates (−10, −7) kpc]. Although not seen in M51, this is very similar to some of the structure seen in M81 (Kendall et al. 2008). Identifications of bifurcations with pattern speed resonances (e.g. Elmegreen et al., 1989) generally require the bifurcation to occur as one proceeds radially outwards, along the arm. We see both in our simulations.
Figure 7. The column density of the gas disc is shown for model A (1 per cent warm gas) after 279, 290, 301, 309 and 320 Myr. The left-hand panels show the galaxy face on (in the $xy$ plane in our coordinates) whilst the right-hand panels show the galaxy along the line of sight (i.e. in the $xz$ plane) where the positive $z$ direction is towards us. The panels indicate that the current position of the companion apparently at the end of a spiral arm is a coincidence, whilst the left-hand panels highlight the evolution of the spiral structure, and interarm structure over much shorter time-scales compared to Fig. 4.
was nowhere near the spiral arm. In the direction along the line of sight (right-hand plots), the companion galaxy is passing through the plane of the disc, from behind to in front of M51. We can also see the evolution of the large branch in the spiral arm, marked B in Fig. 5. The branch is due to material shearing away from the spiral arm, and its presence and location change with time. Thus, unlike Elmegreen et al. (1989), who suggest branches in M51 lie at the 4:1 ultraharmonic resonance of some global pattern speed, we instead suggest they are temporary features, due to the chaotic dynamics, and evolve from material sheared from the spiral arms. We discuss the formation of branches in more detail in Section 4.1.4.

Finally, it has been noted in some observations that there may be an oval distortion in the inner region of M51 (Pierce 1986; Tosaki et al. 1991; Zaritsky, Rix & Rieke 1993). An oval region is apparent in our simulations at \( r \approx 1 \) kpc, with aspect ratio 2:1.

4.1.2 The structure of the disc with a higher fraction of warm gas, and with cold gas

We focus our analysis on model A, presented in Fig. 4 since this was the most stable, with less fragmentation and few sink particles forming. However, before discussing this model in more detail, we first describe the structure in models B and C.

In addition to our main model, we also ran calculations with 10 per cent warm gas (model B) and 0.1 per cent cold gas (model C). The model with 10 per cent warm gas represents a more realistic gas fraction for the galaxy. However, both models B and C were considerably less stable, and formed many more sink particles. Consequently, it was not possible (or appropriate) to run these calculations for as long. We show the structure of the disc at 180 Myr for these two simulations, as well as the case with 1 per cent warm gas (model A) in Fig. 8. The structure for both models with warm (\( 10^4 \) K) gas is very similar (left-hand and middle panels). This is perhaps not that surprising as \( Q_s \) for both models is fairly high. There are some small differences – the spurs are more compact, presumably because the gas is less gravitationally stable (and in fact unlike model A, the spurs tend to contain sink particles). There is generally more local collapse in the model with 10 per cent warm gas and consequently 32 sink particles have formed at this point. The final panel in Fig. 8 (right-hand panel) shows the disc with 0.1 per cent 100 K gas. As expected, there is much more fragmentation than in the models with warm gas. Again widespread collapse occurs in the disc, and after 180 Myr, 184 sink particles have formed.

4.1.3 Evolution of spiral modes

We consider specifically how the spiral structure of the disc changes with time by computing the amplitude of the spiral modes. We calculate the Fourier amplitude of each spiral mode according to Theis & Orlova (2004):

\[
C_m = \frac{1}{M_{\text{disc}}} \left| \int_0^{2\pi} \int_{R_{\text{in}}}^{R_{\text{out}}} \Sigma(R, \theta) R \, dR \, e^{-i m \theta} \, d\theta \right|.
\]

where \( M_{\text{disc}} \) is the mass of either the stellar or gas disc and \( \Sigma \) is the corresponding surface density. We calculate the Fourier amplitudes over annuli of the disc, between \( R_{\text{in}} \) and \( R_{\text{out}} \). Using cylindrical coordinates, \( R \) is the distance from a point to the centre of mass of the galaxy, and \( \theta \) is the angle which subtends to the centre of mass, measured anticlockwise round the galaxy. We did not perform any rotational transformations prior to obtaining the Fourier transforms – the galaxy is still inclined with respect to the line of sight.

We show the amplitude of the modes versus time in Fig. 9 for the whole of the disc (taking \( R_{\text{in}} = 0 \) kpc and \( R_{\text{out}} = 10 \) kpc). The amplitudes of the modes increase during the interaction, and as expected, the \( m = 2 \) mode is the dominant mode. However, the \( m = 2 \) mode is not substantially higher than the other modes, particularly at later times. For the gas, there is even less difference between the \( m = 2 \) and other modes. This comes about because the azimuthal distribution of the gas density is very spiky (Fig. 11).

In Fig. 10, we plot the amplitudes versus time at different radii in the disc. Here, we take annuli of width 2 kpc, about 3, 5 and 10 kpc. We only show the amplitudes for the stars, but the gas shows similar behaviour. From this figure, it is evident that the \( m = 2 \) spiral structure takes longer to develop at smaller radii. This might be due to radial propagation, or it might be because the strength of the tidal forces decreases strongly with radius (note that for the \( R = 10 \) kpc plot, the Fourier amplitudes are not particularly meaningful at later times since the companion is located within 10 kpc). From viewing a movie of the stellar distribution, there is no obvious break in the stellar arms with time. This suggests that the tidal interaction is solely responsible for the inner structure, in agreement with Toomre (1977) and Salo & Laurikainen (2000b). For the gas, however, the main spiral arms are not always continuous, and it is possible (at earlier times) to have shorter sections of spiral arms in the inner disc overlapping the main tidally induced spiral arms.

The lack of a dominant \( m = 2 \) mode is surprising, given that the column density plots (Figs 4 and 5) show an obvious two-armed spiral pattern, both in the gas and stars. However, this does appear

![Figure 8](https://academic.oup.com/mnras/article-abstract/403/2/625/1180363)
The spiral mode amplitudes are shown for the whole of the disc versus time. The top panel is for the stellar (disc) component and the lower for the gas component. The $m = 2$ mode is generally highest, though surprisingly not substantially higher than the other modes, especially for the gas. The reason for this is evident from Fig. 11, where it can be seen that although the azimuthal structure is predominantly double-peaked ($m = 2$), it is sufficiently spiky, and the arms are sufficiently offset, a lot of power in higher values of $m$ is necessary to Fourier-decompose the azimuthal distributions.

In addition to the Fourier amplitudes, we show azimuthal profiles of the density in Fig. 11. We determine the mass averaged volume density ($\rho$) over an annulus of width 1 kpc, divided into 64 sections azimuthally. The figure shows the density at times of 120, 180, 240 and 300 Myr. At 120 Myr, the interaction is still at an early stage, so as expected there is no obvious two-armed pattern, though Fig. 11 and the column density plot (Fig. 4, top middle) indicate that there is one prominent spiral arm in the gas, due to the interaction. The density profiles generally show that the arms are considerably more peaked than sinusoidal curves. In some cases (e.g. $r = 5$ kpc, at 180 Myr or $r = 3$ kpc at 300 Myr), there is also a considerable degree of substructure in the gas. Furthermore, the main arms may be of unequal densities (e.g. $r = 5$ kpc, 240 Myr) and not necessarily symmetric. As we remarked above, this explains the relatively low amplitude of the $m = 2$ mode in relation to the other modes.

4.1.4 Origins of substructure and spurs

The later part of this paper focuses predominantly on comparisons with observations, but beforehand we briefly consider the origins of spurs and branches which lie between the main spiral arms. As mentioned in the introduction, gaseous spurs could be due to perturbations in the underlying stellar disc, or occur as GMCs experience shear when they leave the spiral arms. Numerical simulations of grand design spirals have largely neglected the first hypothesis, as they have assumed an underlying stellar potential, rather than incorporating a live stellar component. Alternatively, for a quasi-steady structure driven by some fixed pattern speed, spurs can occur at specific resonances in the disc.

We investigate the origins of substructure in the disc further by tracing back the gas which constitutes a large branch at the time of 300 Myr. Fig. 12 shows the gas at earlier times of 256 and 271 Myr. At 271 Myr, the gas lies in a clump along the spiral arm, which then becomes sheared into the branch we see at 300 Myr. The origin of the clump in the spiral arm at 271 Myr could be due to gravitational instabilities, which may potentially lead to fragmentation along the spiral arms, and in turn to spurs. However, this does not appear particularly likely, first since as mentioned in
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Figure 11. These panels show azimuthal plots of the stellar and gas densities at times of 120 (top), 180 (second), 240 (third) and 300 (lower) Myr. The mass averaged density is calculated from annuli of width 1 kpc, which are positioned at 3 (left), 5 (centre) and 7 (right) kpc, and both the gaseous (solid) and stellar (dotted) densities are shown. The azimuthal angle is calculated anticlockwise round the disc (in the direction of flow). At the earliest time, the interaction is only commencing, so there is no dominant two armed structure. Though the gas and stellar peaks are generally correlated, which is not surprising if they are generated by gravitational instabilities simultaneously. After 180 Myr, both the gas and stars now have two peaks. However, at the later times there tends to be substructure in the gas which leads to multiple peaks as well as the main spiral arms.

Section 2.2.2, the gas has a relatively high $Q$. Moreover, as Fig. 8 indicates, there is not a significant difference in structure between the models with 1 and 10 per cent gas (A and C), implying that self-gravity of the gas is not regulating the structure. A second possibility is cloud collisions. However, the formation of large clumps in this manner also seems unlikely when the temperature of the gas ($10^4$ K) is high (Dobbs & Bonnell 2006), since the gas is largely smooth. Nevertheless, the gas in these models is clumpy, not because the gas is cold, but rather due to the flocculent spiral arms induced at earlier times by gravitational instabilities in the stellar and gaseous components. Thus, flocculent spiral arms merge with the tidally induced spiral arms to form clumps, which are then sheared into branches or spurs, which in turn seed clumpy structure in the next spiral arm.
In this figure, we focus on the formation of a large secondary harmonic, which appears in the simulation. Gas particles are selected from the branch, and then shown at two earlier time frames (left) whilst all the gas in the locality is shown on the right-hand column density plots. The branch originates from a clump of dense gas in the spiral arm which gets sheared in the interarm region. This in turn originates from substructure in the disc.

A third option is that the clumpy structure along the spiral arms is associated with compressive tidal forces (Renaud et al. 2008), which could account for structure at predominantly larger radii, a possibility that we will address in a later paper.

4.1.5 Comparison of spurs with M51

The surface densities of spurs in the 1 and 10 per cent warm gas models are $10^{-3}$ and $10^{-2}$ g cm$^{-2}$, respectively, or 4.5 and 45 M$_\odot$ pc$^{-2}$. The surface densities of spurs seen in M51 are ~50 M$_\odot$ pc$^{-2}$ (Corder et al. 2008). Thus, the features found in our 10 per cent gas model are approaching the surface densities of spurs in M51, although the surface densities are deliberately low in our models to avoid gravitational collapse.

4.2 Stellar spiral arms and the offset between stars and gas

There have been numerous studies of the offset between different tracers in M51 (e.g. Tilanus & Allen 1989; Rand & Kulkarni 1990; Petit et al. 1996; Patrikeev et al. 2006). The CO is typically seen upstream of H$_\alpha$, and the offset interpreted as the time for stars to form (Tamburro et al. 2008). Density wave theory, i.e. the assumption that the stellar arms rotate more slowly than the gas, predicts that the CO should also be upstream of the underlying old stellar population (Roberts 1969; Gittins & Clarke 2004), although this is dependent on the properties of the model, e.g. sound speed of the gas, strength of the potential (Slyz, Kranz & Rix 2003; Dobbs 2007). Observations of CO overlaid on optical images of M51 indicate such an offset for one spiral arm, though oddly for the other they are coincident (e.g. Schinnerer et al. 2004).

In Fig. 13, we show the column density of the stars (in the disc only), and overlay contours of the gas column density. As expected, the stellar distribution is much smoother, and the spiral arms much broader compared to the gas. Also shown on Fig. 13 is a $K$-band image (which traces the old stellar population) of M51 from Hitschfeld et al. (2009), which again shows good agreement with the stellar distribution from our simulations. Similar to the gaseous arms, the stellar arms in the simulations are wound slightly further than in the observations due to adopting a too high rotation curve initially (Section 2.2).

Fig. 13 does not indicate any obvious offset between the gas and stars. The main departures of the gas from the stellar component are interarm features. A similar conclusion can be drawn from Fig. 11, which shows that the stellar and gaseous peaks tend to be coincident. Any offset between peaks of stellar and gas density in azimuth are temporary, and tend to be localized, e.g. at $R = 5$ kpc, one gas arm lies downstream of the stars (higher $\theta$) whilst the other is essentially coincident. At 240 Myr, one arm is still largely coincident (if anything, upstream) whilst the other has split into two separate peaks.

We determine the offset more systematically by locating the peak of the gas and stellar spiral arms. However, rather than use the $m = 2$ Fourier amplitude, which implicitly assumes symmetric spiral arms and the dominance of the $m = 2$ harmonic, we fit Gaussians to our azimuthal density profiles. As can be seen from the column density plots and Fig. 11, the spiral arms may often be asymmetric. We took density profiles over annuli of width 1 kpc, similar to those shown in Fig. 11. We used a routine in Numerical Recipes (Press et al. 1992) to fit a function of the form

$$\rho(\theta) = A_1 \exp \left( -\frac{(\theta - B_1)^2}{C_1}\right) + A_2 \exp \left( -\frac{(\theta - B_2)^2}{C_2}\right) + A_3,$$

with the amplitudes of the spiral arms given by $A_1$ and $A_2$, the offsets by $B_1$ and $B_2$ and the dispersions by $C_1/\sqrt{2}$ and $C_2/\sqrt{2}$.

The position of the spiral arms is shown versus radius in Fig. 14, for the gas and stars at five different times during the interaction. We took annuli from 1–8 kpc, but at the innermost radius, it was often impossible to fit the distribution to two peaks, indicating that in our model the spiral structure was not strongly induced at such small radii. The error bars in Fig 14 correspond to the width of the Gaussian peak for each arm. In nearly all cases, the stellar and gaseous spiral arms are coincident within the error bars, and, in particular, at the present-day time of 300 Myr. Had we used the errors of the fit instead, the error bars would have been smaller, typically about one third the size shown in Fig. 14. At most time frames, however, the two types of arms would still coincide within the smaller errors.

Kinks in the positions of the gaseous spiral arms are either due to a sharp dip in the spiral amplitude between the inner and outer parts of the annulus, which results in an overestimate of the azimuthal angle of the peak, or occur where the spiral arm bifurcates. There is a slight tendency for the shock to be upstream of the stellar arms at smaller radii and downstream at larger radii. However, if anything,
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4.3 Pattern speeds of the spiral arms

One of the implicit assumptions in Lin-Shu density wave theory is that the spiral arms have a coherent pattern which rotates at a fixed pattern speed. However, recent observations by Meidt et al. (2008) have been unable to find a single pattern speed; rather they assign different pattern speeds to different radii. In an attempt to retain some contact with density wave theory, they suggest that there may be multiple spiral arm modes in the disc, but also agree that their results can be explained by a winding pattern. The most obvious interpretation of their results is the latter, and even more simply, that there is no global pattern speed. This can be seen from our simulations, e.g. by comparing the galaxy at times of 180 and 300 Myr (Fig. 17), where it is evident that the spiral arms are visibly winding up.

We use the results of our Gaussian fitting to find the pattern speed of the arms from our simulations, simply taking \( \Omega_p = \frac{d\theta}{dt} \) at each radius \( R \). In Fig. 15, we show the pattern speed for the stars and gas versus radius, accompanied by a similar figure from Meidt et al. (2008). We show the pattern speeds for each arm, as we do not assume they are necessarily the same. Fig. 15 shows that the pattern speed is not constant with radius. Rather the pattern speed decreases with radius. For Fig. 15, we calculate the pattern speed between times of 180 and 300 Myr. Taking 240 to 300 Myr produces a similar result but with larger error bars. We note that our pattern speeds agree roughly with those determined by Meidt et al. (2008), lying between 25 and 50 kpc km s\(^{-1}\) compared to 50 kpc km s\(^{-1}\) at radii between 2 and 4 kpc and 25 kpc km s\(^{-1}\) between 4 and 5 kpc. Egusa et al. (2009) also measure a pattern speed of 30 kpc km s\(^{-1}\).

In the simulations, the pattern speed of one arm starts relatively flat, then drops at 4.5 kpc, corresponding again to the kink observed in Fig. 5.

5 COMPARISON WITH OBSERVATIONS OF DENSITY AND VELOCITY

In this section, we make a comparison between our results and some of the analyses presented in Shetty et al. (2007). Shetty et al. (2007) note some discrepancies between their observations and density wave theory, in particular, large circular and radial velocities. We follow the procedures outlined in Shetty et al. (2007) for analysing M51. They show plots of column density on a log \( R \) versus azimuth space, and fit straight lines to the spiral arms, which assumes an underlying shape of the arms to be that of a equiangular spiral. They then plot velocity against an angle \( \psi \), where \( \psi \) is the angle extending from a spiral arm.

We first assessed whether there was a warp in the disc, as Shetty et al. (2007) include the position angle in their analysis. However, although our disc shows a slight warp (see Fig. 16), we considered it would make little difference to our results, at least in the central parts of the disc.

5.1 \( R - \theta \) plots of spiral arms

In Fig. 17, we show the column density of gas (left-hand panels) and stars (right-hand panels) on a polar plot, at times of 180, 210, 240, 270 and 300 Myr. Over time, the spiral arms become shallower, in
both stars and gas, again indicating the pattern is becoming more tightly wound.

We also overplot the positions of the peaks determined from the Gaussian fittings on Fig. 17. From the general shape of the arms, and the positions of the peaks, it is apparent that in many cases, the spiral arms cannot be easily fitted by straight lines, and are therefore not logarithmic. Rather the gradient changes with radius. Sometimes there is a clear, even sharp change in the slope of the spiral arms. For example, at the time of 300 Myr, one arm becomes shallower at larger radii, becoming more tightly wound. At 240 Myr, one arm displays the opposite behaviour, becoming more open at larger radii. The figure also shows that the two arms are often asymmetric, displaying different gradients. At 270 Myr, the structure of the gas is very messy, hence the disparity between positions of the gas and stellar arms seen in Fig. 14.

We compare in more detail the gas column density with a Hα plot from Shetty et al. (2007) in Fig. 18. Our results display considerably more structure than the observations. This may simply be a consequence of higher resolution and/or a consequence of the simplicity of our treatment of the interstellar medium (ISM). Also for both the simulations and observations (Shetty et al. 2007), it is difficult to pick out the spiral arms at low (R < 3 kpc) radii.

There is a specific example of a deviation from logarithmic behaviour at the point marked A. Here, there is a kink in the spiral arm, and the gradient becomes shallower. This in fact corresponds to the point marked A in Fig. 6, a feature apparent in both the model and observations. At this point, if the inner arm continued, it would be much more open than observed. Instead, rather than continue with the same pitch angle, the arm becomes more tightly wound. We postulate again that the inner arm is longer lived (from the first crossing of the perturber) whilst the outer spiral arm is much more recent (Fig. 8), thus it is not surprising the sections have different pitch angles, and different pattern speeds.

Interestingly, there is also a bifurcation at the point marked A in Fig. 18. This is the branch marked B in Fig. 6, which is actually turning radially inwards. Although there is no such corresponding feature in the observations, there is nevertheless what appears to be a similar structure below A (marked B), on the next spiral arm, which also moves radially inwards.

### 5.2 Radial velocities

Here, we calculate the radial velocities of the gas. Shetty et al. (2007) plot the average radial velocity versus azimuth, and find large radial motions in the disc, and furthermore large net radial motions at different radii. If the disc obeys standard density wave theory, we would expect no large radial motions, and certainly no net radial motions.

In Fig. 19, we show the radial velocity versus ψ, the angle between spiral arms. This formalism follows Shetty et al. (2007), so ψ = 0 is located approximately on a spiral arm. We also plot the density in Fig. 19, and both are averaged over a 1 kpc band placed at r = 2 (upper), and r = 4 kpc (lower) at times of 180 and 300 Myr. The radial velocities do not show particularly good agreement with Shetty et al. (2007). In Shetty et al. (2007), the radial velocities tend to be positive, whereas ours are a mixture of positive and negative. This could indicate that the orbit of NGC 5195 is too tightly bound in our simulations. The magnitudes of our radial velocities are very high, even compared to Shetty et al. (2007), and although the velocity tends to dip at high density, the profiles...
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Here, we show the pattern speeds of the gaseous (solid) and stellar (dotted) spiral arms (top panel) with error bars. We plot both arms (i.e. two gaseous arms and two stellar arms) separately, as we do not assume they have the same pattern speed. The pattern speed is calculated using the locations of the density peaks (shown in Fig. 14) at 180 and 300 Myr. Also shown is the angular velocity of the stars (red dashed line) and \( \Omega \pm \kappa / 2 \) (blue dashed lines). The lower panel shows a corresponding plot from Meidt et al. (2008), who used the Tremaine Weinberg method to determine the pattern speed in the inner regions of M51. Reproduced by permission of the AAS.

In Fig. 20, we plot the net radial velocity versus radius, at different times. At all times, there are substantial net radial velocities, particularly at larger radii. The figure also indicates that the radial motion fluctuates between inwards and outwards, indicating the disc is compressing and expanding. The net radial velocity in Shetty et al. (2007) varies from 0 to 30 km s\(^{-1}\) for radii \( R < 4 \) kpc, but varies according to the assumed position angle. Our results typically show half this range for \( R < 4 \) kpc, and tend to show a net negative velocity, which again may suggest that NGC 5195 is too gravitationally bound in our simulations.

Figure 16. This figure shows the inclination angle (top) and position angle (lower) against radius. The disc is slightly warped, but by less than 10.3\(^\circ\) for radii within 5 kpc, where observations are focused.

We also capture the larger scale structure, including the extensive tail of H\(_1\).

6 DISCUSSION

We have modelled the galaxy M51 and its interaction with its companion NGC 5195, focusing primarily on the dynamics of the gas, and secondly the stellar disc. The tidal interaction produces spiral arms in the stars and in the gas. The resulting spiral structure shows excellent agreement with that of M51, and we have even successfully reproduced individual kinks and branches identified in M51.

6.1 Density ‘waves’

The spiral structure found in interacting, and other, galaxies is often interpreted in terms of ‘density wave theory’. There is, however, much ambiguity in the literature as to what is meant or understood by the phrases ‘density waves’ or ‘density wave theory’. Before proceeding, it is important to clarify the underlying physical concepts and also the terminology we employ in this paper with regard to the spiral structure we see in galaxies and in our simulations. What we say here is a simplification of the more thorough and detailed analysis to be found in Chapter 6 of Binney & Tremaine (1987). Our discussion will focus on the structure apparent in the stellar disc as it is in the stellar disc that the structures are excited and maintained. The gas for the most part merely responds to the time – and space – varying potential of the stars. Because the orbits of the gas elements cannot intersect without producing shocks, the gas acts as an amplifier for identifying the underlying stellar gravitational potential. In addition, the gaseous response is easier to observe.

6.1.1 Material spiral arms

The simplest concept is that of material spiral arms. Consider a galaxy in which all the stars in the disc are on circular orbits, and ignore the self-gravity of the stars. That is, we assume the contribution to the potential in which the stars are moving comes from the bulge and the halo. Suppose at a particular instant one attaches a flag to each of the stars which lie along a diameter in...
Figure 17. These plots show the column density of the gas (left-hand column) and stars (right-hand column) in log $R$ versus $\theta$ space. For logarithmic spirals, we would expect to see straight lines indicating the spiral arms. This is often not the case, particularly at later times (e.g. 210, 300 Myr). Instead, the slope changes as the arms become more or less tightly wound. Even when the arms can be fitted approximately by straight lines (e.g. 180 Myr), the gradient of each appears to differ. Also shown on these plots are the density peaks found using Gaussian fits, with 1σ error bars.

This galaxy. Then, at a later time, because the rotation rate $\Omega(R)$ is a decreasing function of radius $R$, the flags will form a pattern in the shape of a trailing spiral arm. This is a material spiral arm and will wind up locally at a rate $|d\Omega/d\ln R|$. Because $d\Omega/dR < 0$, the arms are trailing spirals. Because typically the gas in the disc of a galaxy is moving highly supersonically, radial pressure gradients are negligible and the angular velocity of the gas is almost identical to that of the stars. Thus, to a first approximation, the
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6.1.2 Kinematic density waves

The next simplest concept is that of kinematic density waves (Binney & Tremaine 1987, section 6.2). These occur when, as we assumed above, the self-gravity of the stars is negligibly small. The nomenclature is misleading because they are not actually waves; there is no oscillatory behaviour, no restoring forces and they do not propagate (the group velocity is zero). Consider the galaxy described above, and consider a star in a circular orbit at radius $R$. Give this star a small radial impulse. Then, to linear order, the stellar orbit is an ellipse, with one of its foci at the centre of the galaxy (an $m = 1$ perturbation). The star orbits the centre of the galaxy with frequency $\Omega(R)$ and its distance from the centre of the galaxy in the radial direction oscillates with frequency $\kappa(R)$ where $\kappa$ is the epicyclic frequency, given by

$$\kappa^2(R) = \frac{d\Omega^2}{dR} + 4\Omega^2,$$

and in general $\kappa > \Omega$. Thus, in the inertial, non-rotating frame, the orbit is not closed, but appears to precess (retrogradely) at a rate $\Omega - \kappa$. However, in a frame which rotates (progradely) at a rate $\Omega_{ILR}(R) = \Omega(R) - \frac{1}{2}\kappa(R)$, the orbit is closed. In this frame, the orbit, to linear order, takes the form of an ellipse with centre coincident with the centre of the galaxy (an $m = 2$ perturbation).

Since this star’s orbit is non-circular, by conservation of angular momentum, it slows down when it is farthest from the centre. By considering this star and its near neighbours, we can see that this means that its neighbours get closer to it at this point, or, in other words, the stellar density is enhanced there. To illustrate this, imagine that we attach a light to this star, and make it flash each time the star reaches its greatest orbital extent. Thus, when the light is on, it represents a region of enhanced density. Then, in the frame rotating with angular velocity $\Omega_{ILR}$, the light flashes with period $2\pi/\kappa$ but at points in this frame which are fixed either side of the centre.

Now consider a set of stars which are initially uniformly distributed around the circular orbit at radius $R$, and which are subject to a perturbation by an object orbiting at some larger radius, thus the perturbing object has some angular velocity $\Omega_{\text{pert}} < \Omega$. To simplify
matters, suppose that the effect of the perturbation is to give each star a small radial impulse at the moment when it is closest to the perturber (an $m = 1$ perturbation$^2$). Also give each star a light which flashes when its orbit is at its greatest extent. Then, in the frame rotating with angular velocity $\Omega_{ILR}$, we would see a succession of flashes, either side of the centre, whose positions advance in azimuth at a rate $\Omega_{pert} - \Omega_{ILR}$. Suppose the perturber has an angular frequency $\Omega_{pert} = \Omega_{ILR}$, then the succession of flashes are all at the same fixed points in this frame, either side of the centre. In other words, we see a steady light each side of the centre. This would then represent a steady $m = 2$ pattern of density which, in the inertial frame, rotates with angular velocity $\Omega_{ILR}$.

For a more general case, the perturber will induce a temporal Fourier component, which coincides with $\Omega_{ILR}$ at a given radius $R$. This excites the $m = 2$ density pattern (of angular velocity $\Omega_{ILR}$) as described above. Extending over all radii, the effect of the perturbing galaxy is to induce a coherent $m = 2$ density enhancement across the disc, rotating with $\Omega_{ILR}(R)$. In general, it turns out that

$$\frac{d\Omega_{ILR}}{dR} < 0.$$  \hspace{1cm} (6)

Thus, just as for the material spiral arms, these density enhancements form a density structure in the shape of an $m = 2$ trailing spiral arm. At each radius, the density maximum rotates with a local pattern speed $\Omega_p(R) = \Omega_{ILR}(R)$.

Such a structure is called a kinematic density wave. It appears to be called a wave because the stars (and also therefore the gas) move through the density maxima (indeed at a rate $\Omega - \Omega_{ILR}$), and so the particles forming the arms change with time. But the term wave is misleading, because the structure so formed does not propagate. The term kinematic pattern might be more appropriate.

The importance of these patterns is twofold. First, they are $m = 2$ and so are generically induced by tidal perturbations (just as the spiral arms as density waves to and outwards at radii $m = \Omega/\kappa - (6)$). This is a consequence of the lack of leading spiral arms is that the proposed feedback mechanism, by which global modes are maintained by the conversion of leading to trailing arms (Mark 1976), does not appear to operate.

6.1.3 Spiral density waves

Now consider what happens to a kinematic density pattern if we allow the stars which form it to be mildly self-gravitating. Then, the spiral density pattern gives rise to a corresponding spiral gravitational potential. This means that the pattern, which was previously being sheared out by differential precession, is now able to show some coherence. For example, the stars in the gravitational maxima now feel mutual attraction which counteracts the differential shear. This has two effects: (i) the local rate of precession of the pattern is modified, indeed now $\Omega_p > \Omega_{ILR}$ and (ii) the pattern now becomes a genuine wave in that it is able to propagate in the radial direction.

The radial group velocity, $V_g$, of such waves is given by Binney & Tremaine (1987), Chapter 6.2.4:

$$V_g/R\Omega = f \frac{\Delta R}{3.36} \frac{\Omega}{\dot{\Omega}}.$$  \hspace{1cm} (7)

$^2$Note that for a tidal interaction, as we have in this paper, an $m = 2$ perturbation is dominant. In this case, we would introduce an impulse to the star closest to, and the star farthest from the, perturbed galaxy. Thus, an $m = 2$ pattern again occurs, but induced at both the nearest and opposite side from the perturber simultaneously.

$^3$The central bars in barred galaxies also produce $m = 2$ perturbations which can set up similar patterns, but we do not consider those here.

where $\Delta R = \sigma_g/\kappa$ is the radial excursion of stellar orbits, given a radial velocity dispersion $\sigma_g$, $Q = (\sigma_g/\kappa)/(3.36\, G\, \Sigma)$ is the usual Toomre parameter which measures the strength of self-gravity, and $f$ is a dimensionless factor which can be derived from the relevant dispersion relation.

6.1.4 Density wave theory of spiral arms

The aim of density wave theory, as propounded by Lin & Shu (1964), was to show that the large-scale spiral structure within a galaxy can be self-maintained in a quasi-steady state, without input from external perturbations. If true, then this could account for grand design spiral structure seen in galaxies without the need to appeal to internal bars or external tidal interactions. Because, in the presence of self-gravity, density waves propagate radially, it seemed a reasonable proposition that the spiral pattern seen in grand design spiral galaxies might correspond to a global, long-lasting, self-sustaining spiral mode, with some pattern speed $\Omega_p$ independent of radius. For such a fixed pattern speed, stellar spiral density waves are able to propagate only at radii between the inner Lindblad radius ($R_{ILR}$) at which $\Omega_{ILR} = \Omega_p$ and the outer Lindblad radius ($R_{OLR}$) at which $\Omega + \frac{1}{2}\kappa = \Omega_p$. Between these two radii lies the corotation radius ($R_{CO}$) at which $\Omega = \Omega_p$. In order to set up such a spiral density mode using spiral density waves, it is necessary for the waves to be able to propagate to and fro between $R_{ILR}$ and $R_{OLR}$ (analogous to the mechanism of setting up a vibrating mode on a violin string requiring travelling waves to be able to communicate between the two ends of the string). The major problem for this theory is that it has never been shown how this can be achieved in practice. There are a number of reasons for this. An example of one is that a major observational advance since this theory was first propounded is that it is now known that all observed spiral structures in galaxies consist of trailing spiral arms. Such structures propagate only inwards at radii $R < R_{CO}$ and outwards at radii $R > R_{CO}$. Thus, using the observed spiral arms as density waves to set up a spiral ‘mode’ of the kind observed is not feasible. A further consequence of the lack of leading spiral arms is that the proposed feedback mechanism, by which global modes are maintained by the conversion of leading to trailing arms (Mark 1976), does not appear to operate.

6.1.5 Illustration

An illustration of the response to be expected by a stellar galactic disc to a tidal perturbation can be found in the paper by Oh et al. (2008). They consider the response of a mildly self-gravitating disc of stars to a perturber which flies by on a parabolic orbit. Although there are some limitations to their models (they adopt two-dimensional thin disc models and fix the position of the perturbed galaxy), they find that the dominant response at late times is $m = 2$, and as can be seen from their Fig. 14, the temporal behaviour of the response at late times has a pattern speed equal to $\Omega_{ILR}(R)$. This is true for their model A2$^2$ in which stellar self-gravity is set to zero, so that the response corresponds to a kinematic density pattern and cannot propagate radially, and also for their model A2 which has mild stellar self-gravity and shows evidence for some inward radial propagation.
gas discs to the interaction is strongly time-dependent and dynamic. Thus, trying to interpret the response in terms of full density wave theory, with spiral modes of fixed pattern speeds (if they exist) is not a fruitful way to proceed. From our detailed analysis, we find compelling evidence that M51 does not fit the Lin-Shu hypothesis of spiral density wave theory. This has been hinted at in recent observations (Shetty et al. 2007; Meidt et al. 2008) (see also Buta & Zhang 2009). Rather than being a rigid pattern, the spiral pattern continuously evolves throughout the interaction. The lengths, amplitudes and azimuthal separation of the arms change with time. Moreover, the spiral pattern winds up over a time-scale \( \gtrsim 100 \) Myr (cf. Merrifield, Rand & Meidt 2006). Thus, there is no well-defined global pattern speed for the spiral arms; there is, rather, a radially decreasing pattern speed of the spiral arms (Fig. 15). There we see that the radial variation in pattern speed is about \( \Delta \Omega_p (R) \approx 20 \, \text{km s}^{-1} \, \text{kpc}^{-1} \) which corresponds to a wind up time-scale of \( 2 \pi / \Delta \Omega_p \approx 300 \) Myr. Indeed what we are seeing is similar to the findings of Oh et al. (2008). The pattern speeds we find for the arms (both stellar and gaseous) (Fig. 15) lie slightly above the curve \( \Omega_m (R) \) which is what we expect for a tidally induced kinematic density pattern with the addition of mild self-gravity. The angular frequency of the perturbing galaxy (NGC 5195) varies as it proceeds along its orbit in the range 10–30 km s\(^{-1}\) kpc\(^{-1}\), with the highest frequencies corresponding to the closest approaches, and so to the strongest tides. The response frequencies lie mainly in this range.

We describe a highly chaotic picture of the dynamics of M51 and NGC 5195. The companion orbits M51 twice, with two close non-coplanar encounters producing a predominantly \( m = 2 \) spiral response during each passage. As seen from Fig. 17, the main spiral arms become more difficult to distinguish with time, and show abrupt changes in pitch angle. In addition, dynamical interactions between the tidal impulses and the arms and between the spiral arms themselves lead to apparent bifurcations in the form of secondary arms, branches and spurs. We show that these interarm branches are simply material shearing away from the spiral arm. The simulations produce branches which fork away from a spiral arm both inwards and outwards along the spiral arm. From the detailed evolution of the disc, we find that features including the kink along one spiral arm and large interarm branches evolve relatively quickly (over 10s of Myr). They are not long-lasting features compared to the arms themselves. Thus, for example, the interpretation of spiral arm bifurcations and other structure in terms of 4:1 ultraharmonic or other resonances (Elmegreen et al. 1989; Chakrabarti et al. 2003) in such tidally driven structure is not a fruitful exercise.

A number of authors have attempted to use the offsets between the stellar spiral potential dips and the shocks in the gas, delineated, for example, by molecular gas and/or star formation, as a means of estimating the relative flow speed of the (stellar) spiral pattern and the gas, often relying on the basic assumption that the spiral has a fixed pattern speed (e.g. Westfall 1998; Gittins & Clarke 2004; Kendall et al. 2008; Buta & Zhang 2009; Martínez-García, González-Lópezlira & Bruzual-A 2009). While this can be a useful procedure in barred galaxies (Buta & Zhang 2009), where one might expect there to be an overall pattern speed driven by the rotation speed of the bar, it is likely to be less so in interacting galaxies. We have already noted that in flocculent galaxies it is expected that there is essentially no offset between the stars and the gas (Dobbs & Bonnell 2008). From our simulations of a strong tidal interaction, we have found (Figs 11, 14 and 17) that there is little offset between the gaseous and stellar arms, and that when offsets can be discerned they can have either sign, and moreover the sign of the offset can vary with radius. This comes about because in the case of M51 the tidal interaction is strong and still on-going, and thus the responses both in the stars and in the gas are still strongly dynamical.

### 6.2.1 Swing amplification

Previous simulations have highlighted the role of swing amplification in maintaining spiral structure in interacting systems (Hernquist 1990; Donner & Thomasson 1994). With sufficient self gravity, spiral arms subject to shear become narrower and more pronounced. The stellar spiral arms in our simulation appear to be fairly broad (Fig. 13), suggesting that swing amplification is not operating. Ideally, we would need to run calculations without self gravity to confirm whether the stellar spiral arms are essentially just kinematic features, or whether they are indeed amplified. However, we can estimate the importance of swing amplification by calculating

\[
\lambda_y = \frac{4 \pi G \Sigma}{\kappa^2}. \tag{8}
\]

Swing amplification becomes effective once \( \lambda_y < 3 \). For our simulations, \( \lambda_y = 2 \pi R/m \) where \( m = 2 \) for a two armed spiral, hence

\[
X = \frac{\pi R \kappa^2}{4 \pi^2 G \Sigma^2} \tag{9}
\]

We can rewrite this as

\[
X = \frac{3.36 Q v_x \kappa}{4 \pi \sigma \Omega^2}, \tag{10}
\]

where \( v_x \) is the circular velocity and \( \sigma \) the stellar velocity dispersion. Taking \( Q = 1 \) (Fig. 2), \( \kappa/\Omega \sim 1.7 \) and \( v_x/\sigma \sim 8 \), typical for our simulations, gives \( X = 3.6 \). More generally, these quantities vary across the disc, but \( X \) lies between 3 and 4 for all but the innermost regions, where \( X \) is higher.

Thus, there may be some swing amplification occurring in the spiral arms of our simulations, but it is unlikely to have a large effect. This is compatible with previous simulations which found that the mass of the disc needs to be about that of the bar for swing amplification to become important (Sellwood &Carlberg 1984; Byrd et al. 1989), as well as the results of Oh et al. (2008). Our simulations in fact suggest that swing amplification is not vital to producing well-defined spiral arms, since the gas response naturally provides narrow, dense spiral arms (as we observe), even though the stellar arms are much broader.

### 6.3 Caveats

Although the overall dynamics of the interaction seems to be well accounted for by our simulations, the details require several important caveats.

As pointed out throughout the paper, the orbit differs from that found by Theis & Spinneker (2003), since we adopt a live halo as opposed to a static potential. In future, we should ideally use an orbit which takes into account dynamical friction. However, this significantly increases the computational time for the MINGA code, and is impractical when embarking on this project. This effect is likely exacerbated by underresolving the halo in our simulations, to reduce computational time. Furthermore, we only modelled the companion galaxy as a point mass, again to concentrate computational resources to modelling the disc of the M51 galaxy. We expect that modelling the companion galaxy may also change the orbit of the two galaxies.
We used a very simple model of the ISM in M51. We ignore the fact that, in general, the ISM is likely to be multiphase and interactive. The warm phase can condense to become cool, the cool phase can give rise to star formation in dense regions, and the resultant stellar feedback can recycle cool gas back to being warm. Moreover, we ignore pressure in the ISM due to magnetic fields and cosmic rays, and dynamical feedback from supernovae, etc. We expect stellar feedback would change the distribution of the gas primarily on smaller scales, though supernovae may well produce holes and further substructure in the disc. Magnetic fields will act to reduce the amount of substructure (Dobbs & Price 2008), but may not be sufficient to alter the larger scale branches seen in our simulations. We note as well that in our main model, we assume a gas temperature of $10^4$ K. The gas in M51 is predominantly molecular, and will therefore tend to be significantly colder. In our model with cold gas, the disc undergoes excessive fragmentation. It may well be that including stellar feedback, and/or magnetic fields adds to increase the local pressure of the gas, more similar to our $10^4$ K model, thus reducing fragmentation and local collapse.

It also needs to be borne in mind that the relative positions of the gaseous shock and the spiral potential minimum can depend on the sound speed in the gas. For example, if the thermal energy in the gas is comparable to the potential energy drop in the arm, it is possible for the shock to be upstream of the potential minimum (Roberts, 1969), whereas if the thermal energy is much less than the depth of the gravitational potential of the arm, the shock is to be found downstream of the potential minimum, where the gas is decelerated as it climbs out of the potential well (Dobbs et al. 2006). We note, however, that we find from our models for M51 differences in assumed sound speeds do not result in large differences in the resulting large-scale gas distributions (Fig. 8).

As a first attempt at modelling M51, we have only performed relatively low-resolution simulations. Even so we have been able only to carry out one long time-scale run. It is evident that a better model of the internal structure of M51 would be required to obtain better agreement between the observations and the simulations. Higher resolution simulations will be required to analyse the details of molecular cloud and star formation in M51. Also, for the current simulations, we have only shown a scenario where the companion galaxy lies on a bound orbit and eventually merges with the main galaxy. A related question is what happens for a more generic case when the orbit is not bound, and how long does the spiral pattern (in the stars and gas) persist?

ACKNOWLEDGMENTS

We thank Rob Kennicutt and Sarah Kendall for useful discussions. We would also like to thank an anonymous referee for a careful reading of the manuscript. We are also grateful to Alar Toomre for sending comments on an earlier draft of this paper, and making publicly available his 1981 conference proceedings.

CLD thanks the University of Vienna for funding a visit to the Institute for Astronomy. CLD also acknowledges support from the Institute of Astronomy (Cambridge) visitors’ grant, and JEP similarly acknowledges support from the University of Exeter visitors’ grant. This work, conducted as part of the award ‘The formation of stars and planets: radiation hydrodynamical and magnetohydrodynamical simulations’ made under the European Heads of Research Councils and European Science Foundation European Young Investigator (EURYI) Awards scheme, was supported by funds from the Participating Organisations of EURYI and the EC Sixth Framework Programme.

The calculations reported here were performed using the University of Exeter’s SGI Altix ICE 8200 supercomputer. CLD acknowledges Dave Acreman for the maintenance and support of the Exeter supercomputer. Figures included in this paper were produced using SPLASH, a visualization package for swi that is publicly available from http://www.astro.ex.ac.uk/people/dprice/splash/ (Price 2007).

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