Synthetic H\textsubscript{i} observations of a simulated spiral galaxy

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ABSTRACT

Using the TORUS radiative transfer code we produce synthetic observations of the 21 cm neutral hydrogen line from an SPH simulation of a spiral galaxy. The SPH representation of the galaxy is mapped onto an AMR grid, and a ray tracing method is used to calculate 21 cm line emission for lines of sight through the AMR grid in different velocity channels and spatial pixels. The result is a synthetic spectral cube which can be directly compared to real observations. We compare our synthetic spectral cubes to observations of M31 and M33 and find good agreement, whereby increasing velocity channels trace the main disc of the galaxy. The synthetic data also show kinks in the velocity across the spiral arms, evidence of non-circular velocities. These are still present even when we blur our data to a similar resolution as the observations, but largely absent in M31 and M33, indicating those galaxies do not contain significant spiral shocks. Thus the detailed velocity structure of our maps better represent previous observations of the grand design spiral M81.

Key words: methods: numerical – radiative transfer – radio lines: galaxies – galaxies: individual (M31, M33)

1 INTRODUCTION

The last decade has seen huge advances in computational modelling of galaxies. Allied with observational developments this provides increased opportunities to study and understand the interstellar medium (ISM). Comparing models and observations provides valuable insight into the dynamics and evolution of the ISM, in particular translating the physics incorporated in the simulations into observable features.

High resolution hydrodynamical and magnetohydrodynamical models can now begin to examine how the interstellar medium is swept into giant molecular clouds, and ultimately forms stars (Wada & Norman 1999, Shetty & Ostriker 2006, Wada 2008, Dobbs 2008, Tasker & Tan 2009, Dobbs et al. 2008). The ability of supernovae to trigger molecular cloud formation can also be studied using numerical models (de Avillez & Berry 2001, Dib et al. 2006). At the same time, high resolution surveys now provide data on the distribution and properties of molecular clouds (Heyer et al. 1998, Engargiola et al. 2003, Rosolowsky 2007, Brunt et al. 2009). Advances in observational capability also provide increased insight into the characteristics of the ISM in external galaxies e.g. recent H\textsubscript{i} observations of the nearby spiral galaxies M31 (Chemin et al. 2009) and M33 (Putman et al. 2009) and the irregular galaxies Holmberg II (Rhode et al. 1999) and the LMC (Kim & Park 2007). Additionally, statistical properties of H\textsubscript{i} in galaxies can be studied using larger samples obtained through surveys (Walter et al. 2008, Tamburro et al. 2009). Thus comparing simulations and observations is particularly timely; however in order to provide a direct comparison the output of the simulations needs to be processed to produce the same data products, such as spectral line datacubes and maps, which are obtained from observations.

An obvious application of such synthetic observations is to test whether numerical models can reproduce the structure of the interstellar medium seen in observations, thus synthetic observations provide an important validation test of numerical models. Synthetic observations may also be generated with very high spatial resolution compared to observed data, hence simulations can show what we will view in nearby galaxies with future facilities. Moreover, synthetic observations are derived from simulated objects with known properties (e.g. density, temperature, velocity) whereas when dealing with real observations these properties are calculated from the observations. Within the Milky Way we commonly rely on radial velocities to determine distances, however for simulations, features can readily be located both in velocity and cartesian space. Hence working with synthetic obser-
vations makes it easier for features in the observations to be related to the physical processes from which they result. An important effect in this paper is the impact of velocity structure on H\textsc{i} observations.

Previous comparisons of velocity structure in simulated spiral galaxies with observed data range from simply identifying clouds and plotting their position in velocity space \citep{Dobbs2006, Baba2009}, to sophisticated radiative transfer models \citep{Chakrabarti2009, Narayanan2009} and synthetic galactic plane surveys \citep{Gomez2004, Douglas2010, Dobbs2006} plotted the distribution of molecular clouds in velocity space to show that they reproduce the distribution in the Outer Galaxy reasonably well. \citep{Baba2009} plotted the location of cold gas using the velocities of the gas in their models and an assumed rotation curve, and highlighted the disparity with the actual location of the gas, illustrating the so called ‘finger of God’ effect. On larger scales, \citep{Narayanan2009} and \citep{Chakrabarti2009} perform analysis on SPH (smoothed particle hydrodynamics) simulations of interacting galaxies, using radiative transfer codes to determine CO emission and spectral energy distributions respectively. \citep{Gomez2004, Douglas2010} generate synthetic galactic plane surveys and compare their velocity structure to real observations from the Leiden/Dwingeloo H\textsc{i} survey and the Canadian Galactic Plane Survey respectively.

On extragalactic scales H\textsc{i} is a powerful tracer used to analyse galactic structure, e.g. tracing spiral arms and tidal tails, and showing holes and cavities in the ISM. Synthetic H\textsc{i} maps have been constructed previously \citep{Wada2006, Dib2005}, though for irregular rather than spiral galaxies. These studies compared synthetic H\textsc{i} maps with data from Holmberg II and the LMC, concluding that the structure in these galaxies is primarily due to a combination of turbulence and thermal and gravitational instabilities, with supernovae contributing to a lesser degree. In this paper, we produce synthetic H\textsc{i} maps of a simulated grand design spiral galaxy \citep{Dobbs2008}, in which the structure is instead dominated by spiral density waves, and the gas velocities reveal information about the spiral structure. Velocity gradients reveal streaming motions, due to the presence of spiral density waves (or at least stellar spiral arms which rotate at lower \(\Omega(r)\) than the stars, see \citep{Dobbs2009, Wada2004}) which produce spiral shocks in the gas.

As our model galaxy is a perfectly isolated, grand design system, which has no effects from interactions with companions or high velocity clouds, we expect to see only effects due to spiral shocks. \citep{Visser1980} first showed kinks in the velocities along the spiral arms in M81, due to non-circular motions, typically with a magnitude of a few 10’s of km s\(^{-1}\) \citep{Adler1996}. We expect to see similar effects in our synthetic observations and our idealised model system allows us to study these effects without the additional complexity introduced by environmental interactions.

We used an SPH code to model the galaxy (unlike the grid based calculations by \cite{Dib2005} and \cite{Wada2000}), which we then combine with \textsc{torus}, a grid-based radiative transfer code. Thus we have the further complication of converting between SPH and a grid code. We begin in Section 2 by describing the method used to generate synthetic observations, including the SPH to grid conversion. The technique is used to produce spectral cubes for galaxies with orientations like M31 and M33, which are assessed and compared to real observations of M31 and M33, in Section 3 as a means of validating the method. Although these galaxies do not display grand design structure to the extent of M81 (indeed M33 is a flocculent spiral), we have access to high resolution H\textsc{i} data for these nearby systems.

\section{Method}
This section describes the method used to generate the synthetic observations, starting from the SPH simulation of the spiral galaxy and going through to the production of a 21 cm spectral line cube.\section{SPH simulation of the spiral galaxy}
\subsection{Calculations}
The calculation used in this paper was set up as described in \citep{Dobbs2008}, but we also provide a description below. The calculation constitutes one of a series investigating structure and the formation of molecular clouds in spiral galaxies, and most notably, includes a full thermodynamical model of the ISM, and the conversion between atomic hydrogen and molecular hydrogen, necessary for producing our synthetic observations. We did not however include self gravity or magnetic fields, although these have been the subject of previous papers \citep{Dobbs2008, Dobbs2009}. The presence of magnetic fields is expected to inhibit the formation of structure in the galactic disc and reduce the strength of spiral shocks \citep{Roberts1970, Dobbs2009}, resulting in a smoother distribution of gas, and spiral arms which are wider and less dense. Conversely, self gravity will increase density in regions which are already overdense (enhancing the formation of structure in the gas) and increase the likelihood that gas in dense regions will be fully molecular.

The calculation used as the basis for our synthetic observations was performed using smoothed particle hydrodynamics (SPH), a Lagrangian fluids method. We modelled a gaseous disc, whilst the stellar component was included as an external potential. This external potential includes a stellar disc and halo, and incorporates a 4 armed spiral component from \citep{Cox2002} with a pattern speed of 2 \(\times\) 10\(^{-6}\) rad yr\(^{-1}\) and a pitch angle of 15\(^\circ\). The amplitude of the stellar spiral perturbation is 1.1 \(\times\) 10\(^{12}\) cm\(^{-2}\) s\(^{-2}\).

We did not model the whole disc, but restricted the domain to radii between 5 and 10 kpc, primarily to increase resolution. The gas particles were initially distributed randomly, with a scale height of 400 pc and a temperature of 7000 K. The particles were assigned circular velocities according to the disc potential, with a 6 km s\(^{-1}\) velocity dispersion.

The surface density of the galaxy was 10 \(M_\odot\) pc\(^2\), including helium, which is comparable to the average surface density at the solar radius \citep{Wolfire2003}. We used 8 million particles in the calculation thus giving a resolution of 500 \(M_\odot\) per particle.

We followed the thermal evolution of the gas using a
model for the heating and cooling of atomic and molecular gas taken from Glover & Mac Low (2007). This model incorporated many processes, including cooling from fine structure emission, gas-grain cooling, and heating from photodissociation and cosmic ray ionisation of atomic hydrogen.

We also included the formation of molecular hydrogen, as well as CO. We evolve the abundance of molecular gas according to a prescription given by Bergin et al. (2004), and provide a full description in Dobbs (2008). We assign each particle a molecular gas fraction, and calculate the rate of formation of H$_2$ on grains, and the rate of destruction of H$_2$ by photodissociation and cosmic ray ionization, to update the molecular gas fraction after each time step. We noted in our previous paper that determining the photodissociation rate requires an estimate of the column density in order to take into account self shielding. As described in Dobbs (2008) we adopt a constant length of 35 pc to calculate the column density, which is the average distance to a B0 star in the Milky Way. Given the H$_2$ fraction for a particular particle, we determine the H$_i$ density used for this paper from $n(H) = n - 2n(H_2)$, where $n(H), n(H_2)$ and $n$ are the number densities of H$_i$, H$_2$ and the total number density.

2.1.2 Evolution of galaxy disc

The evolution of the gas disc is described fully in Dobbs et al. (2008) but we also provide a brief summary here. As the disc evolves, the spiral pattern emerges and narrow spiral arms develop. Most of the gas cools from the initial temperature of 7000 K and typically 70 % of the gas (and all the gas in the spiral arms) is < 150 K. Clumps of cold gas accumulate into more massive clouds as they pass through a spiral shock. The molecular gas (which constitutes around 30 % of the total gas) lies predominantly in the spiral arms, and typically forms from the atomic medium over time scales of order 10 Myr. As dense clumps leave the spiral arms, they are sheared into short spur. Some cold clumps, or spur, are able to survive between the arms, though they do not tend to contain much molecular gas. We do not have observational measurements of the proportions of warm and cold gas in external galaxies. The fractions in our simulations are not dissimilar from the solar neighbourhood, the only region for which there is an observational indication of the fractions of cold and warm H$_i$ (Heiles & Troland 2003). In the absence of observational evidence to the contrary we can only assume that other nearby large spiral galaxies are not vastly different in terms of the amount of gas in different phases.

We run the simulation for a total of 320 Myr. For the comparisons in this paper, we take the output at a time of 250 Myr, by which point the distribution of gas in different phases, and the amount of molecular gas, has reached a roughly steady state.

2.2 AMR grid construction

We use the radiative transfer code TURUS (Harries 2000) to generate synthetic H$_i$ observations. TURUS is a grid-based radiative transfer code that uses Adaptive Mesh Refinement (AMR) to provide variable spatial resolution. TURUS can perform radiative transfer calculations, using the Monte Carlo method of Lucy (1999), and can also generate spectral energy distributions, images and spectral cubes. The code has frequently been applied to models of stellar discs and performs well in benchmark tests, even at high optical depths (Pinte et al. 2009).

To generate a synthetic H$_i$ data cube we first need to convert from the particle representation of SPH to the AMR grid representation of TURUS. The TURUS AMR grid is constructed using the octree method in which the grid initially comprises eight cells (one octal) with two cells in each spatial dimension. The grid is refined by specifying a condition which determines when a cell is split into a further eight cells. For this calculation the grid cells were split if the mass of the cell exceeded a given limit (mass per cell limit). A mass per cell limit gives higher spatial resolution in regions of high density, which is similar to the effective spatial resolution of the SPH method. A maximum H$_i$ mass per cell of 2.5 x 10$^{16}$ g (1260 M$_\odot$) was used to split the grid, which resulted in an AMR grid comprising 678815 octals and 4751706 unique cells. This mass per cell limit corresponds to approximately 9 SPH particles per grid cell (for particles with an average atomic hydrogen fraction) and was chosen to give sufficient spatial resolution to represent the important features of the model galaxy, within the constraints of the available computer memory. Should a calculation require higher spatial resolution, the mass per cell limit can be decreased to give smaller cells in the AMR grid (Douglas et al. 2010).

Once the grid structure has been generated H$_i$ density, temperature and velocity values are assigned to each cell using values from the SPH particles, smoothed with an exponential kernel. Construction of an AMR grid from SPH particles, using this method, was tested by Acreman et al. (2010) using an azimuthally symmetric circumstellar disc benchmark. In the case of a spiral galaxy it is also necessary to represent accurately structure, such as spiral arms, clouds and spurs, which are not present in an azimuthally symmetric disc. We found that the method of Acreman et al. (2010) gave a good representation of structure within the disc and a good representation of the total H$_i$ mass provided one modification was made. The method normalises density values by the sum of the SPH kernel weights, if the sum of the weights exceeds a specified threshold, in order to reduce noise in the interior of the distribution. Acreman et al. (2010) normalise when the sum of the weights exceeds 0.3, but we found this value gave a total H$_i$ mass which was too large, by 11 per cent, relative to the H$_i$ mass of the SPH particles. The SPH to grid conversion was performed with a range of normalisation thresholds, in order to test the impact on the representation of the total H$_i$ mass, and the results are plotted in Fig. 1. A normalisation threshold of 0.5 gives a mass which is too small by only 0.3 per cent, so we use this value as the threshold above which the SPH kernel smooth is normalised.

The H$_i$ density in the galaxy midplane, as represented on the AMR grid, is shown in Fig. 2(a) for purposes of comparison a similar plot from the original SPH particles is shown in Fig. 2(b) where the particles have been rendered using the SPLASH plotting software (Price 2007). This figure shows that the spiral arms are well represented in both cases and the SPH particle to AMR grid conversion has been effective in preserving these features. Figure 3 again shows
Figure 2. H\textsc{i} density (in g/cm\textsuperscript{3}) in the galaxy midplane, as represented on the \textsc{torus} AMR grid (left) and as represented with SPH particles (right). The spiral arms are well represented in both cases demonstrating that the conversion from SPH particles to AMR grid preserves spiral arm structure.

Figure 3. H\textsc{i} density (in g/cm\textsuperscript{3}) in the galaxy midplane, as represented on the \textsc{torus} AMR grid (left) and as represented with SPH particles (right). The AMR representation has the grid overplotted. This figure is similar to Fig. 2 but shows a smaller domain to emphasize that the smaller scale structures are well represented on the grid.

the midplane density in the grid and SPH representations, but for a reduced domain, with the AMR mesh over plotted in Fig. 3(a) to emphasize how the enhanced AMR resolution in regions of high density enables good resolution of small scale features.

2.3 Opacity and emissivity calculation

The relatively simple nature of the H\textsc{i} 21 cm line transition means that once the density and temperature of a cell are known the emissivity and opacity can be calculated and stored on the AMR grid. The opacity $\kappa_\nu$ is given by
The method is similar to that of Rundle et al. (2010) and is carrying out ray tracing operations through the AMR grid. Once the AMR grid is set up a spectral cube is generated by the density and temperature values on the AMR grid. The emissivity is calculated from the opacity using Kirchoff’s law (\( \epsilon_\nu = k \nu B_\nu \)) and the Rayleigh-Jeans approximation giving

\[ \epsilon_\nu = \frac{3c^2 A_0}{32\pi k \nu_0} \frac{n(H)}{T_S} \phi(v). \]  

(1)

\[ \kappa_\nu = \frac{3c^2 A_0}{32\pi k \nu_0} \frac{n(H)}{T_S} \phi(v). \]  

(Rohls & Wilson 2004) where \( c \) is the speed of light, \( h \) is Planck’s constant, \( A_0 \) is the Einstein probability emission coefficient, \( k \) is the Stefan-Boltzmann constant, and \( \nu_0 \) is the frequency of the \( \text{H}_i \) transition. The number density of \( \text{H}_i \) \((n(H))\) and the excitation temperature \((T_S)\) are taken from the density and temperature values on the AMR grid. The emissivity is calculated from the opacity using Kirchoff’s law \((\epsilon_\nu = \kappa_\nu B_\nu\) where \(B_\nu\) is the Planck formula\) and the Rayleigh-Jeans approximation giving

\[ \epsilon_\nu = \frac{3c^2 A_0}{32\pi k \nu_0} \frac{n(H)}{16\pi} \phi(v). \]  

(2)

The profile function \(\phi(v)\) is assumed to be a Gaussian with a thermal width \(\sigma_{\text{th}}\) given by

\[ \sigma_{\text{th}}^2 = \frac{kT}{m_H}. \]  

(3)

where \(T\) is the temperature of the grid cell and \(m_H\) is the mass of a hydrogen atom. Unlike Wada et al. (2000) we do not add a term to represent microturbulence as the majority of the gas in our simulation is at temperatures where we expect the thermal line width to dominate (see fig. 4 of Dobbs et al. 2008). As the contribution of the line profile to the opacity and emissivity depends on the velocity channel under consideration the line profile is calculated during the radiative transfer step and is not stored on the AMR grid.

### 2.4 Radiative transfer calculation

Once the AMR grid is set up a spectral cube is generated by carrying out ray tracing operations through the AMR grid. The method is similar to that of Rundle et al. (2010) and is summarised below.

A ray is traced through the grid, starting from the observer’s position and proceeding along the ray direction to distances further from the observer. The contribution of the grid cell to the pixel brightness is calculated using the emissivity and opacity taken from the AMR grid. Each cell contributes to the intensity in the pixel but with absorption by the accumulated optical depth between that cell and the observer. There is an iterative procedure in which the intensity of the pixel is updated from an old value \(I_i\) to a new value \(I_i'\) with the contribution of a grid cell according to

\[ I_i' = I_i + S_\nu \left(1 - e^{-\tau} \right) e^{-\tau_{\text{total}}}. \]  

(4)

where \(S_\nu = \frac{\lambda^2}{2\pi^2}, \) \(dr\) is the optical depth of the cell and \(\tau_{\text{total}}\) is the total optical depth between the cell and the observer.

The model grid is rotated to represent a galaxy with the required position angle and inclination angle. A number of parallel rays, one per pixel, are traced through the grid to calculate emission for each pixel in each velocity channel of the cube. The ray trace through each individual cell is sub-divided into smaller steps to give better sampling of the velocity gradient across the cell. If the velocity difference across the cell, projected onto the direction of the ray, is \(\Delta v\) then the ray trace is decomposed into \( 5 \frac{\Delta v}{c} \) separate steps.

The synthetic observations are converted to units of brightness temperature, using the Rayleigh-Jeans approximation, by multiplying by \(\frac{\lambda^2}{2\pi^2}\), where \(\lambda\) is the wavelength of the transition. Continuum emission from the cosmic microwave background is included as a blackbody component with a temperature of 2.73 K.

### 3 RESULTS

Our technique was used to generate synthetic spectral line data cubes resembling radio observations of M31 and M33, two Local Group spiral galaxies, for which arcminute-scale 21 cm observations were available. The model galaxy was not set up to model M31 or M33 specifically, so although we expect the synthetic data to reproduce general features seen in H I observations of external galaxies we do not make a detailed quantitative comparison with the observations. However comparisons of the synthetic data with observed data do provide a valuable validation test of the method.

#### 3.1 M31

The model galaxy was given an inclination angle of 77.5 degrees and a major axis position angle of 220.0 degrees (measured clockwise from North) in order to match the observed orientation of M31 in equatorial co-ordinates (see fig. 9 of Chemin et al. 2009)). The position angle of the model galaxy is offset by 180 degrees so that it rotates in the same direction as M31. A velocity offset of \(-300 \text{ km/s}\) was applied to the data cube velocity channels consistent with the systemic velocity determined by Chemin et al. (2009). The orientation of the galaxy can be seen in the column density plot in Fig. 4(a). The spectral cube was constructed using 600 spatial pixels of size 10\(^{20}\) cm and 250 velocity channels over a range of 840 km/s. The velocity channels were chosen to give comparable velocity resolution to the observations of Chemin et al. (2009).

The emission from the synthetic data cubes is plotted as “renzograms” (Fig. 4(b) and Fig. 4(c)) which plot a single
Figure 4. Top left: column density from the model galaxy orientated to be like M31. Top right: contours of constant brightness temperature in different velocity channels (renzogram) overlaid on summed intensity for the model galaxy. There is one contour per velocity channel with different velocity channels indicated by different colours (−500 km/s for the red contour and −100 km/s for the black contour). The data have been blurred with a one pixel Gaussian. Lower left: as for top right but blurred with a three pixel Gaussian. Lower right: renzogram plot from the M31 observation of Chemin et al. 2009.
A spatially averaged line profile from the simulated Figure 5. A spatially averaged line profile from the simulated M31 galaxy (solid line, left side y-axis). The average is taken over the whole data cube and background subtracted. A similar spatially averaged line profile from the observations of Chemin et al. [2009] is also plotted (dashed line, right side y-axis).

level contour map for several velocity channels. The contours are of constant brightness temperature with different velocity channels shown in different colours. The contours are at 50 km/s intervals starting at −500 km/s (red contour) and ending at −100 km/s (black contour). The contours are overlaid on a grey scale plot of brightness temperature summed over all velocity channels. These synthetic data cubes have been spatially blurred with a Gaussian filter of 1 pixel (Fig. 4(b)) and 3 pixels (Fig. 4(c)) width to simulate the effect of observing with an instrument with finite spatial resolution (1 pixel corresponds to 0.14 arcmin and 3 pixels corresponds to 0.43 arcmin at a distance of 785 kpc). A similar plot of the observational data presented by Chemin et al. [2009] is shown in Fig. 4(d). As the rotation velocity of the model galaxy (220 km s$^{-1}$) and the rotation velocity of M31 (230 km/s in the outer galaxy Chemin et al. [2009]) are similar, the velocity channels which are contoured in Fig. 4(d) are the same as in Fig. 4(b) and Fig. 4(c).

A good general agreement is seen between the synthetic and real data whereby the galaxy’s main outer disc is traced as the velocity channels increase. The synthetic data with the least blurring (i.e. the highest spatial resolution) show structure associated with the spiral shock in the disc. This structure is not particularly evident in the observed data for M31. This may be because of lack of resolution (it is also more difficult to distinguish the spiral structure in our 3 pixel blurred image) or simply because the spiral shocks are too weak or nonexistent. In fact Efremov [2009] argues that there is a spiral shock in one arm, but not the other, based on observations of stellar gradients across spiral arms and the distribution of star complexes, so the presence of spiral shocks in M31 is rather ambiguous.

A line profile from the synthetic data, blurred with a one pixel Gaussian and spatially summed over the whole galaxy, is plotted in Fig. 5 (solid line). A similar observed global line profile from the data of Chemin et al. [2009] is also plotted (dashed line). As the circular velocity of the model galaxy is similar to the rotation velocity of M31 the modelled line profile can be quantitatively compared to the observed line profile. Both profiles show peaks at around −100 km s$^{-1}$ and −500 km s$^{-1}$ although M31 has a slightly greater circular velocity, so the peaks are slightly further apart. The observed profile is more extended than the synthetic profile, in that the emission falls away less rapidly towards -600 km/s and zero; the effect is more pronounced towards more negative velocities. Figure 7 of Chemin et al. [2009] shows that material with velocities around -600 km/s is to be found at approximately one third of the disc outer radius (0.8 degrees from the centre of M31). This material would lie within the 5 kpc inner radius of our model galaxy and would not be represented. The observed profile also shows asymmetric structure between the peaks, which is not present in the synthetic line profile, which we also expect to come from the central regions of the galaxy. There is likely to be complex structure present in the inner regions of a real galaxy, which is not represented in our model galaxy, and this structure can noticeably affect the global line profile.

Many of the line profiles from individual pixels contain structure which is better represented in data with higher velocity resolution. The synthetic data cube was regenerated using 1000 velocity bins, over the same velocity range, and the effect on an example line profile can be seen in Fig. 6 (solid line with squares is 1000 velocity channels, dashed line with crosses is 250 velocity channels). This profile is taken from $x = -1.59$ kpc, $y = 3.91$ kpc which is in one of the spiral arms. The line profile from the data cube with 250 channels shows that the shape of the line is much less accurately represented than with 1000 channels and some features of the line (e.g. between −165 and −170 km/s) are not represented in the lower resolution case. The presence of structure with intrinsically narrow velocity widths was observed in VLA observations of M31 by Braun [1990] and our model galaxy exhibits similar narrow velocity widths in its spectral features. For accurate quantitative work the data which are output from the radiative transfer code must be represented with sufficient velocity resolution to represent accurately these narrow features of the line profiles.
the radiative transfer code to the intensity derived from the emissivity along the required line of sight. In order to match the observed orientation of M33 in equatorial co-ordinates. These values are representative of the H I distribution fitted by [Corbelli & Schneider 1997]. A velocity offset of $-180$ km/s was applied to the data cube velocity channels in order to match the observed approach velocity (Corbelli & Schneider 1997). The cube comprises 600 spatial pixels of size $10^{-20}$ cm and 500 velocity channels over a range of $360$ km/s.

A column density plot is shown in Fig. 7(a) which shows a more face-on view than M31 (see Fig. 4(a)). The simulated data overlaid on a grey scale plot of summed intensity, are shown in Fig. 7(b) and Fig. 7(c) for synthetic data blurred with a 1 pixel and 6 pixel Gaussian respectively (1 pixel corresponds to 0.15 arcmin and 6 pixels corresponds to 0.92 arcmin at a distance of 730 kpc). The minimum velocity is $-342$ km/s and contours increase in steps of $36$ km/s to a maximum of $-19$ km/s. A corresponding contour plot from the observational data of Putman et al. (2009) is shown in Fig. 7(d). As M33 has a smaller rotation velocity than our model galaxy (100 km/s compared to 220 km/s) the velocities which are contoured in Fig. 7(d) have been scaled by a factor of 100/220 compared to the velocities contoured in the synthetic data plots. For both the synthetic data and the observed data the contour interval is 16 per cent of the rotation velocity.

We again get a good qualitative comparison between the synthetic and real observations, taking into account that we do not model the inner 5 kpc of the galaxy. The general behaviour of the contours is as expected i.e. the main disc of the galaxy is traced out as velocity increases and there are perturbations in the velocity contours due to non-circular velocities. Figure 7(b) clearly shows perturbations in the contours associated with the spiral arms whereas lower resolution data (Fig. 7(c)) show much less detail but exhibit a broadening of the contours in the region of the spiral arms. Our simulated galaxy is a grand design spiral which shows non-circular motions due to the presence of spiral shocks. In contrast M33 is a flocculent spiral with a relatively weak spiral perturbation. The structure in M33 is instead largely due to gravitational instabilities and supernovae feedback which are not included in the model galaxy. Moreover even in the absence of spiral shocks there are likely to be non-circular motions due to other mechanisms (e.g. tidal interactions and warps). The simulated data show what would be observed in an idealised case where a strong spiral perturbation dominates the structure of the galaxy.

### 3.3 Comparison to optically thin limit

In the optically thin limit the absorption term in the radiative transfer equation can be neglected i.e.

$$\frac{dl}{ds} = -\kappa l + \epsilon \approx \epsilon$$

and the intensity in an image pixel can be found by simply integrating the emissivity along the required line of sight. In this case the intensity is proportional to the column density. As a validation test of the method the ratio of intensity from the radiative transfer code to the intensity derived from the optically thin approximation was calculated for each pixel in the data cube. The ratio of these intensities should be unity when the optical depth is small, and the optically thin approximation holds, and should decrease below unity as the optical depth increases.

Figure 8 plots the ratio of intensity from the radiative transfer calculation to intensity from the optically thin approximation against optical depth for the simulated M31. Figure 8(a) is from the results presented in the previous section with 250 velocity bins over a range of 840 km/s. Pixels in which the column density is less than $10^{20}$ cm$^{-2}$ are not plotted in order to exclude pixels which are not associated with the galaxy. The intensity ratio at low optical depths is close to unity and there is a trend of decreasing intensity, relative to the optically thin limit, as optical depth increases, as expected. However there is a considerable amount of scatter and there are some points with a ratio greater than unity, up to a maximum value of 1.21. An example line profile from a pixel with a ratio greater than unity is shown in Fig. 9. This pixel is located at $x = -0.972$ kpc, $y = -0.3626$ kpc and is not included in Fig. 8 as the column density is below the cutoff threshold. However it is used here as a clear example of how the velocity integrated emission in a pixel can be overestimated due to a lack of resolution in velocity space. Figure 8(b) shows the same plot as Fig. 8(a) but for the synthetic data cube with 1000 velocity bins. The points with ratios greater than unity are absent and there is less scatter on the distribution. The velocity resolution clearly has a significant impact on the results of this validation test.

A similar plot showing the ratio of the intensity from the radiative transfer calculation to intensity from the optically thin approximation against optical depth for the simulated M33 is shown in Fig. 10. As before with a column density less than $10^{20}$ cm$^{-2}$ are not plotted. The velocity resolution of the synthetic M33 cube is high enough that the comparison with the optically thin limit is good and does not show the scatter seen in the M31 cube when only 250 velocity channels are output.
Figure 7. Top left: column density from the model galaxy orientated to be like M33. Top right: contours of constant brightness temperature in different velocity channels (renzogram) overlaid on summed intensity for the model galaxy. There is one contour per velocity channel with different velocity channels indicated by different colours. The data have been blurred with a one pixel Gaussian. Lower left: as for top right but blurred with a six pixel Gaussian. Lower right: renzogram plot from the M33 observation of Putman et al. 2009.

3.4 Velocity perturbations in renzograms

We develop a simple analytical representation of the velocity perturbations seen in the renzograms, in order to gain a quantitative understanding of how changes in velocity within the galaxy relate to perturbations in renzogram contours. The following analysis uses a cylindrical polar coordinate system with its origin at the centre of the galaxy. The $r$ coordinate represents the distance from the galactic centre in the midplane, the $z$ coordinate is the distance out of the midplane and $\theta$ is the cylindrical polar angle. It is assumed that all gas moves in the azimuthal direction only.

The line of sight velocity, towards the observer, of a parcel of gas is
Figure 8. Ratio of intensity from radiative transfer calculation to intensity from the optically thin approximation, plotted against optical depth (for the simulated M31). Left: from a calculation using 250 velocity bins. Right from a calculation using 1000 velocity bins.

\[ v_{\text{los}} = v_t \cos \theta \sin i + v_{\text{sys}} \]  

(6)

where \( v_t \) is the magnitude of the tangential velocity (velocity in the azimuthal direction) for a given parcel of gas, \( i \) is the inclination of the galaxy and \( v_{\text{sys}} \) is the systemic velocity of the galaxy. For an observation with the systemic velocity subtracted this gas will be seen in velocity channel

\[ v_{\text{ch}} = v_t \cos \theta \sin i \]  

(7)

In the absence of any deviation from a constant circular velocity the renzogram contours have a constant value of \( \theta \). However, the effect of the spiral shock means that in a given velocity channel we expect to see both gas moving at the circular velocity of the galaxy \( (v_t = v_c) \) and other gas which has just passed through a spiral shock (post-shock gas). This causes an azimuthal perturbation in the renzogram contour.

We assume that the effect of passing through the shock is to reduce the speed of this gas to \( v_{\text{ch}} = f v_c \) \( (0 < f < 1) \) without changing its direction. Gas moving at the circular velocity will be seen at a position

\[ \cos \theta_c = \frac{v_{\text{ch}}}{v_c \sin i} \]  

(8)

whereas post-shock gas is seen at a position

\[ \cos \theta_{\text{ps}} = \frac{v_{\text{ch}}}{f v_c \sin i} \]  

(9)

The linear separation in the plane of the disc \( d \) of circular and post-shock gas is given by

\[ d = 2r \sin \left( \frac{\theta_c - \theta_{\text{ps}}}{2} \right) \]  

(10)

which can be re-written, using trigonometric identities and substituting from eqn. 8 and eqn. 9 as

\[ d = 2r \left[ \left( 1 - x^2 \right)^{1/2} - x \left( 1 - \left( \frac{x}{f} \right)^2 \right)^{1/2} \right] \]  

(11)

where

\[ x = \frac{v_{\text{ch}}}{v_c \sin i} \]  

(12)

When viewed on the plane of the sky this distance is reduced, due to projection effects, by a factor of...
\[
\left(\sin^2 \theta + \cos^2 i \cos^2 \theta\right)^{1/2} = \left(1 + \left(\cos^2 i - 1\right) x^2\right)^{1/2}
\]

Hence the angular size of the perturbation in the velocity contour \((\Delta \alpha)\) is

\[
\Delta \alpha = \frac{2r}{D_{\text{gal}}} \left[\left(1-x^2\right)^{1/2} x - x \left(1 - \left(\frac{x}{f}\right)^2\right)^{1/2}\right] \times \left(1 + \left(\cos^2 i - 1\right) x^2\right)^{1/2}
\]

where \(r\) is the distance of the perturbation from the galactic centre and \(D_{\text{gal}}\) is the distance to the galaxy.

At \(x = 0\) (i.e. the channel corresponding to the systemic velocity) there is no velocity perturbation according to eqn. (14). In this channel gas which is moving in circular motion has no line of sight component. As we have assumed that the velocity perturbation is simply a reduction of the circular motion there is no mechanism for changing the line of sight component. In the renzograms derived from the synthetic observations there are perturbations seen in this velocity channel indicating that the velocity perturbation in our model galaxy is not simply a reduction of the circular motion but has another component which affects the line of sight velocity.

The angular size of the velocity perturbations seen in the renzograms (as predicted by eqn 14) is plotted against \(x\) in Fig. 11(a) for four inclination angles; 0 degrees (solid line), 30 degrees (dashed line), 60 degrees (dot-dashed line) and 90 degrees (dotted line). This plot assumes the galaxy is at a distance of 785 kpc (i.e. the distance to M31) with a shock 7 kpc from the galactic centre (representative of our model galaxy). The shock is assumed to reduce the circular velocity by a factor \(f = 0.9\) (i.e. a perturbation of 20 km/s on a 200 km/s circular velocity). A similar plot showing the size of the velocity features in kpc is shown in Fig. 11(b). The predicted size of the features is in agreement with the features seen in the renzograms of the synthetic observations (i.e. a typical size of approximately a kpc). In all cases the size of the velocity perturbation tends towards zero as \(x\) tends towards zero, due to the assumption that the perturbation only affects the circular velocity (as discussed above). As \(x\) increases towards \(f\) the size of the feature increases because the circular velocity has a larger component in the line of sight. The renzograms for our synthetic observations also show larger velocity kinks in channels further from the systemic velocity. There is a change in the sign of \(\alpha\) when \(x\) becomes negative (eqn 14 is an odd function of \(x\)) due to the assumption that the shock always reduces the circular velocity. This results in post-shock gas always moving towards the velocity channel of the systemic velocity (or zero if the systemic velocity has been subtracted). The size of the velocity kinks increases as the inclination angle increases, due to projection effects, however in practice it will be difficult to see these features for nearly face-on cases because very high velocity resolution would be required (for nearly face-on cases the range of \(x\) corresponds to a small velocity range).

### 4 CONCLUSIONS AND FUTURE WORK

We have presented a method for generating synthetic spectral cubes of the 21 cm hydrogen line from SPH simulations of spiral galaxies. The method successfully maps the density, temperature and velocity from the SPH particles onto an AMR grid, while preserving important structures (e.g. spiral arms and spurs) and accurately representing the total mass. Synthetic data cubes are generated using a ray tracing method. The synthetic data show good agreement with observations of M31 and M33 whereby increasing velocity channels trace out the main disc of the galaxy. Velocity contours of the synthetic data show perturbations due to non-circular motions, similar to those already observed in M51 (Adler & Westpfahl 1996; Visser 1980; Rots & Shane 1975), which are not seen in the observations of M31 and M33.

Our model galaxy is a grand design spiral galaxy and shows velocity structure associated with the spiral perturbation. The method of generating synthetic observations can also be applied to simulations in which velocity structure is generated by other mechanisms. Internal mechanisms, such as self-gravity and stellar feedback, can generate velocity structure, and indeed are dominant in flocculent spiral galaxies. External influences can also affect the HI morphology of a spiral galaxy e.g. interactions with a companion galaxy, high velocity clouds or the intracluster medium. As the majority of galaxies reside in groups or clusters, it is likely that external environmental effects will influence the HI structure of most real galaxies; our model galaxy is perfectly isolated and our results show idealised behaviour in the absence of external influences.

A large parameter space could potentially be studied, involving galaxies with different internally and externally generated velocity structure. Some of these aspects can already be modelled (e.g. a galaxy undergoing an interaction, Dobbs et al. (2009)) and some require further model development (e.g. inclusion of stellar feedback, which is ongoing). A large number of models must be run in order to generate the SPP input for the radiative transfer calculation. Once such a library of simulations was available, one could compare these with real observations in order to understand the velocity structure of spiral galaxies. However given the potentially complex nature of the velocity structures generated there would need to be a reliable way of matching an observed galaxy with its counterpart in the synthetic observation library. In our present models, we can relate the strength of the spiral shock, and the inclination of the galaxy, to the size of the perturbations in the renzograms. When we include additional physics, e.g. self gravity and feedback, we can investigate whether these perturbations are still observable (for a given shock strength) or whether they are overwhelmed by other motions in the gas.

Our method has also recently been applied to an observer placed inside the galaxy (Douglas et al. 2010) to generate a synthetic galactic plane survey. HI self absorption features and the conversion of cold HI to molecular clouds, as seen in a real galactic plane survey (e.g. Taylor et al. 2003; Stil et al. 2006), are seen in the synthetic data. A powerful future application of using a simulation for generating a survey is that given a series of time frames we will be able to trace the evolution of molecular clouds, and related observed features, to the physical properties of the material in the cloud. The method can also be extended to generate synthetic observations of other tracer species, such as CO, or dust, for simulated surveys or simulated external galaxies.
Figure 11. Left: Angular size (in arcmin) of velocity perturbations, according to eqn. [14] for a galaxy at 785 kpc with a shock at 7 kpc from the galactic centre. The shock strength parameter is $f = 0.9$. Four inclinations are shown: 0 degrees (solid line), 30 degrees (dashed line), 60 degrees (dot-dashed line) and 90 degrees (dotted line). Right: as for previous figure but with sizes in kpc. The parameter $x$ (see eqn [12]) is the velocity channel scaled by the circular velocity projected onto the line of sight ($v_c \sin i$).

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