Impact of dark matter sub-haloes on the outer gaseous discs of galaxies

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ABSTRACT

Late-type disc galaxies are observed to have extended gas discs that are significantly larger than their optical discs. The Λ cold dark matter (Λ CDM) cosmological model predicts that luminous galaxies, such as the Milky-Way (MW), are hosts to a large number of low-mass dark matter sub-haloes (DMSHs), which are capable of interacting with the discs of galaxies. We aim to understand the kinematic impact of a DMSH collision with the extended gas disc of a galaxy. In order to study this, we use hydrodynamical simulations with a variety of parameters such as galaxy inclination, DMSH mass, and galaxy mass. To analyse the simulation results, we present two-dimensional (2D) kinematic and gas density maps of galaxies to investigate their unique features and structures. Along with this, we also implement a deep learning (DL) model to classify kinematic images of the simulated galaxies as either impacted (by the DMSH) or isolated. Through the use of these techniques, we have found that the impact of the DMSH causes features in both the 2D kinematic and gas density plots, most notably the development of a ~ 1 kpc size H I hole in the gas-rich DMSH impact. Through the study of these maps, we identify certain features and the specific conditions required to induce them. The study of these features is important, as they can be observed with large upcoming H I surveys such as WALLABY and SKA.

Key words: galaxy: evolution – galaxies: haloes – galaxies interaction.

1 INTRODUCTION

Gas-rich disc galaxies are generally observed to have H I diameters significant larger than their optical discs (Broeils & van Woerden 1994), furthermore dwarf galaxies have also been shown to have extended gas discs much larger than their optical discs (e.g. Burstein et al. 1984; Begum, Chengalur & Karachentsev 2005; Schmidt et al. 2014). Such outer parts of galactic gas discs can be influenced by a number of key dynamical processes of galaxy formation and evolution, such as stripping of gas by tidal interaction with other galaxies and by ram pressure of hot intra-cluster medium (e.g. Noguchi 1987; Vollmer et al. 2000), satellite infall (e.g. Hayashi & Chiba 2006), radiative cooling of outer halo/disc gas (e.g. Aumer & White 2013), and tidal torque of triaxial dark matter (DM) haloes (e.g. Bureau et al. 1999; Bekki & Freeman 2002). Furthermore, the physical properties of galaxy-wide star formation (e.g. star formation rate/efficiency) in the outer parts of disc galaxies can have valuable information on the conversion from cold gas to stars in galaxies (e.g. Elmegreen & Hunter 2006). Thus, the outer part of gas-rich disc galaxies can have key historical information on the formation and evolution processes of the galaxies.

One of possibly important physical processes in the outer parts of galactic discs is the dynamical impact of dark matter sub-haloes (DMSHs; e.g. Bekki & Chiba 2006; Hayashi & Chiba 2006). The presence of numerous DM substructures in the DM haloes have been predicted by the Λ CDM model of galaxy formation (e.g. Diemand et al. 2008; Springel et al. 2008). The influence of such DMSH on dwarf galaxies was studied by Starkenburg, Helmi & Sales (2016) and it was found that dark influences can significantly disturb dwarf galaxies and that even a minor merger event can alter the structure and kinematics of a dwarf galaxy. Furthermore, dark satellite impacts have been shown to causes holes in the extended H I discs of galaxies (e.g. Kannan et al. 2012), these holes are however subject to there being a tiny fraction of gas in the companion DMSH. A brief summary of the past works on the dynamical impact of DMSH on galaxies is summarized in Table 1.

However, these previous numerical simulations have not provided theoretical predictions on the two-dimensional (2D) kinematic distributions of cold gas in the outer part of disc galaxies that have recently experienced the DMSH impact. Previous studies did not fully explore the effect of a complete simulation parameter space and its effect on the formation of structures through interaction with a DMSH. Thus, it is not so clear what kinematic signatures such DM impacts have on the outer gaseous discs of gas-rich galaxies. Such signatures of the past interaction between DMSHs and disc galaxies can be observed by ongoing large H I surveys on the physical properties of gaseous discs [e.g. WAL-

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Table 1. Summary of previous works on the interaction between DMSH and outer gas discs of galaxies. These studies investigated the dynamical impact of DMSH on the outer discs of galaxies as well as any significant morphological changes that occur. This paper builds on some aspects of these works and examines in detail the kinematic features caused by DMSH impact on outer gas discs of galaxies.

Authors	Physical impact of DMSH
Bekki & Chiba (2006)	Dark impact results in local fine structures in discs of galaxies, these filaments in the outer parts of the galaxy often exceed the threshold density for star formation.
Chakrabarti & Blitz (2009)	New method for mass determination of a dark satellite using tidal gravitational imprints they leave on gas density of the galaxy.
Bekki (2009)	Dark impact on the formation of the Gould belt, DM clumps impacting their host galaxies can significantly alter star formation histories of their gas cloud.
Kannan et al. (2012)	Holes can be formed in outer discs of galaxy if the DMSH impact has a small fraction of gas. These holes in the disc are surrounded by regions of active star formation.
Starkenburger et al. (2016)	Dark impact on dwarf galaxy causes heating and a disrupted morphology and kinematics. Larger DMSH fractions cause more pronounced impacts.
Tepper-García & Bland-Hawthorn (2018)	A DM free high-velocity cloud can reach the galaxy disc, however, it cannot survive transit. To survive transit, the cloud needs to have a DMSH encompassing it.

Figure 1. Illustration of interaction between the galaxy and DMSH in the model and corresponding detection. We study the kinematic footprint of DMSH collisions on the outer gas discs of galaxies. Impact of DMSHs on the outer discs of the galaxy is expected to cause disruptions, as they can tidally disturb the gas disc. We study this disturbance through the use of 2D kinematic maps of gas, and further the study by using DL algorithms to automatically classify the features.

LABY (Koribalski et al. 2009) project]. Therefore, it is quite important for theoretical studies to predict the possible observable signatures of the impact of DMSHs on the outer gaseous discs of galaxies.

The purpose of this paper is to investigate the dynamical impact that DMSHs have on the outer gas discs of gas-rich disc galaxies. Fig. 1 demonstrates the approach we use for this study, where we analyse the impact of the DMSH on the 2D kinematic and gas density maps of galaxies. To quantitatively capture the perturbations caused by the DMSH on the outer gas disc of the galaxy, we also present a quantitative parameter (F -parameter). We study this scenario with a certain number of changeable parameters such as galaxy inclination, galaxy mass, mass ratio of the companion DMSH, and lastly, the gas richness of the companion. Along with this, we have also implemented deep learning (DL) to classify DMSH interacting galaxies. The need to develop an automatic classification technique is important as upcoming large surveys such as WALLABY (Koribalski et al. 2009) will generate a large number of images, $\sim 600\,000$, and identifying them for DMSH impact by human eye would be a time-consuming process, this is where an automatic classification technique can be useful to efficiently differentiate dark impact galaxies.

The layout of this paper is as follows. We describe the new models for dynamical interaction between the gas discs of galaxies and DMSHs in Section 2. We present the results on the 2D map of

gas distribution and kinematics of disc galaxies that are influenced by dark impact for different representative models in Section 3. We discuss a novel method to detect the observational signatures of the dark impact automatically in Section 4. We summarize our conclusions in Section 5.

2 THE MODEL

2.1 Disc galaxy

The outer gas disc of a galaxy is assumed to interact with a DMSH, such that the physical properties of the gas disc can be dynamically disturbed. To simulate the time evolution of the outer gas discs in galaxies under the impact of DMSHs we use chemodynamical simulation code that can be run on GPU machines (Bekki 2013, hereafter B13). The code combines the method of smoothed particle hydrodynamics (SPH) with gravitational interaction between N -body particles for calculations of three-dimensional (3D) self-gravitating fluids in galaxies. The code also enables us to investigate the formation and evolution of dust and molecular hydrogen (H_2) in disc galaxies (B13), though it is numerically costly to calculate H_2 formation and evolution (i.e. it requires significantly more CPU time in comparison with simulations with no H_2 calculation). For the present study, our main interest is to study the impact of DMSHs on the outer gas discs of galaxies, we do not discuss in detail the evolution of dust and H_2 .

A disc galaxy is assumed to consist of the DM halo, stellar disc, stellar bulge, and gaseous disc. The total masses of DM halo, stellar disc, gas disc, and bulge are denoted as M_h , M_s , M_g , and M_b , respectively. We mainly investigated three different disc galaxy models with different M_h in order to understand how the impact of DMSHs can influence these different mass galaxies. We investigate the Milky-Way (MW) type (labelled as ‘MW’ for simplicity) with $M_h = 10^{12} M_\odot$, we also investigate Large Magellanic Cloud (LMC) type with $M_h = 10^{11} M_\odot$ and ‘Dwarf type’ (‘DW’), with $M_h = 10^{10} M_\odot$. It should be stressed here that these three models have physical properties that are similar to, yet not exactly the same as, those observed for the MW, LMC, and typical dwarfs. The basic parameter values for the fiducial MW-type model M1 can be found summarized in Table 2.

We adopt the density distribution of the Navarro–Frenk–White (NFW) halo (Navarro, Frenk & White 1996) suggested from CDM

Table 2. Description of the basic parameter values for the fiducial model M1.

Physical properties	Parameter values
Total halo mass (host)	$M_h = 1.0 \times 10^{12} M_\odot$
DM structure (host) ¹	$R_{\text{vir}} = 245 \text{ kpc}, c = 10$
Total halo mass (DMSH)	$M_{h,\text{sub}} = 1.0 \times 10^9 M_\odot$
DM structure (DMSH)	$R_{\text{vir,sub}} = 1.2 \text{ kpc}, c_{\text{sub}} = 20$
Stellar disc mass	$M_s = 6.0 \times 10^{10} M_\odot$
Disc scale length	$R_{0,s} = 3.5 \text{ kpc}$
Gas fraction in a disc	$f_g = 0.09$
Bulge mass	$M_b = 10^{10} M_\odot$
Bulge size	$R_b = 3.5 \text{ kpc}$
Gas mass fraction (DMSH)	0
Galaxy interaction	Yes
Initial central metallicity	$[\text{Fe}/\text{H}]_0 = 0.34$
Initial metallicity gradient	$\alpha_d = -0.04 \text{ dex kpc}^{-1}$
Chemical yield	Tsujimoto et al. (1995) for SN van den Hoek & Groenewegen (1997a) for AGB
Dust yield	B13
Photoelectric heating	No
Dust formation model ²	$\tau_{\text{acc}} = 0.25 \text{ Gyr}, \tau_{\text{dest}} = 0.5 \text{ Gyr}$
Initial dust/metal ratio	0.4
H ₂ formation ³	Dependent on D and ISRF (B13)
Feedback ⁴	SN Ia ($f_{\text{bin}} = 0.09$) and SN II
SF ⁵	H-dependent, ISRF, $\rho_{\text{th}} = 10 \text{ cm}^{-3}$
Initial mass function (IMF)	The canonical Salpeter IMF
Mass resolution for stars	$3.0 \times 10^5 M_\odot$
Mass resolution for gas	$6.0 \times 10^4 M_\odot$

simulations:

$$\rho(r) = \frac{\rho_0}{(r/r_s)(1 + r/r_s)^2}, \quad (1)$$

where r , ρ_0 , and r_s are the spherical radius, the characteristic density of a dark halo, and the scale length of the halo, respectively. The c -parameter ($c = r_{\text{vir}}/r_s$, where r_{vir} is the virial radius of a DM halo) and r_{vir} are chosen appropriately for a given dark halo mass (M_{dm}) by using the c - M_h relation predicted by recent cosmological simulations (Neto et al. 2007).

The bulge of a disc galaxy (for the MW type) has a size of R_b and a scale length of $R_{0,b}$ and is represented by the Hernquist density profile. The bulge is assumed to have isotropic velocity dispersion and the radial velocity dispersion is given according to the Jeans equation for a spherical system. Although the bulge-mass fraction ($f_b = M_b/M_s$) can be a free parameter, we mainly investigate the MW-type models with $f_b = 0.17$ and $R_b = 0.2R_s$ (i.e. $R_{0,b} = 0.04R_s$), where R_s represents stellar disc size, we also define the mass fraction of gas $f_g = M_g/(M_s + M_g)$. The radial (R) and vertical (Z) density profiles of the stellar disc are assumed to be proportional to $\exp(-R/R_0)$ with scale length $R_0 = 0.2R_s$ and to $\text{sech}^2(Z/Z_0)$ with scale length $Z_0 = 0.04R_s$, respectively. The gas disc with a size $R_g = 2R_s$ has the radial and vertical scale lengths of $0.2R_g$ and $0.02R_g$, respectively. In the present model for the MW type, the exponential disc has $R_s = 17.5 \text{ kpc}$ and $R_g = 35 \text{ kpc}$. In addition to the rotational velocity caused by the gravitational field of disc, bulge, and dark halo components, the initial radial and azimuthal velocity dispersions are assigned to the disc component according to the epicyclic theory with Toomre's parameter $Q = 1.5$. The vertical velocity dispersion at a given radius is set to be 0.5 times as large as the radial velocity dispersion at that point.

The total numbers of particles used for DM, stellar disc, gas disc, and bulge in a MW-type disc are 700 000, 200 000, 100 000, and

33 400, respectively (i.e. $N = 1033\,400$ is used in total). No bulge is included in the LMC and Dwarf-type models, and so the total particle number is 1000 000 for those two. The softening length of DM halo (ϵ_{dm}) for each model is chosen so that ϵ_{dm} can be the same as the mean particle separation at the half-mass radius of the halo. This method is applied for determining softening length for stellar particles (ϵ_s) in the initial disc of each model. The softening length is assumed to be the same between old stellar, gaseous, and new stellar particles in the present study. The gravitational softening length for dark (ϵ_{dm}) and baryonic components (ϵ_s) are 2.1 kpc and 200 pc, respectively, for the MW-type disc. These values are different in models with different masses.

2.2 Dark matter sub-halo

We adopt a full N -body model for the DMSH, where the DMSH total mass $M_{h,\text{sub}}$ is represented by many collisionless DM particles. The number of particles used for the DMSH is 10^4 for the fiducial model, and for models with different DMSH mass ratios it is given by $10^6 \times m_2$. Gas was added to the simulation via an exponential gas disc with the size given by the formula $17.5 \times (0.001)^{1/2} \text{ kpc}$ for the fiducial model. We model the NFW halo profile as follows:

$$\rho(r) = \frac{\rho_{0,\text{sub}}}{(r/r_{\text{sub}})(1 + r/r_{\text{sub}})^2}, \quad (2)$$

where r , $\rho_{0,\text{sub}}$, and r_{sub} are the spherical radius, the characteristic density of a DMSH, and the scale length of the DMSH, respectively. Previous numerical simulations showed that a DMSH should have a large (Kazantzidis et al. 2004) c -parameter ($c = r_{\text{vir,sub}}/r_{\text{sub}}$, where $r_{\text{vir,sub}}$ is the virial radius of a DMSH). Following these simulations, we adopt $c = 20$ for DMSHs for $M_{h,\text{sub}} = 10^9 M_\odot$.

Bekki & Chiba (2006) showed that DMSHs without gas can cause the formation of gaseous holes or shells in the gaseous discs of galaxies whereas Kannan et al. (2012) pointed out that small fractions of gas within DMSHs can cause formation of quite important gaseous structures. Since the physical origin for this difference is not so clear, in this study we investigate the two cases of DMSHs, with and without gas. It should, however, be noted that the gas of DMSHs can be stripped by warm (hot) gaseous haloes of their host luminous galaxies through ram pressure of the warm gas. Therefore, for this study we focus on models in which the DMSHs have no gas before their interaction with their host galaxy.

2.3 H₂ formation in chemodynamical simulations

The details of the new model for H₂ formation on the surface of dust grains in galaxy-scale chemodynamical simulations have been discussed in previous works by B13. We therefore explain the model for H₂ formation very briefly in the present study. The present chemodynamical simulations include both H₂ formation on dust grains and H₂ dissociation by far-ultraviolet (FUV) radiation self-consistently. The simulations can predict a number of key properties for H₂ formation/destruction at each time-step in a self-consistent manner. The temperature (T_g), hydrogen density (ρ_H), dust-to-gas ratio (D) of a gas particle, and the strength of the FUV radiation field (χ) around the gas particle are calculated at each time-step so that the fraction of molecular hydrogen (f_{H_2}) for the gas particle can be calculated. Since spectral energy distributions (SEDs) of stellar particles around each i th gas particles [thus interstellar radiation field (ISRF)] are estimated from ages and metallicities of the stars by using stellar population synthesis codes for a given initial mass function (IMF) (Bruzual & Charlot 2003), the strength of the FUV-

part of the ISRF can be self-consistently estimated from the SEDs so that χ_i can be derived for the i th gas particle. Using χ_i , D_i , and $\rho_{H,i}$ of the gas particle at each time-step, we can derive $f_{H_2,i}$, where $f_{H_2,i}$ is the molecular gas fraction for each (i th) particle. This $f_{H_2,i}$ is used to determine the gas consumption rate by star formation for each gaseous particle.

2.4 Star formation and feedback

We adopt an assumption that gas particles can be converted into ‘new stars’ if the following three physical conditions are met. The first condition is described as follows:

$$\rho_g > \rho_{th}, \quad (3)$$

where ρ_g is the total mass density of a gas particle and ρ_{th} is a threshold gas density for star formation. The threshold gas density for star formation (ρ_{th}) is set to be 10 cm^{-3} for all models in the present study. This is different from ‘ H_2 -dependent’ star formation (SF) recipe that was adopted in our previous works (B13). The second condition is that the local dynamical time-scale should be shorter than the sound crossing time-scale (mimicking the Jeans instability). The third condition is that the local velocity field is identified as being consistent with gravitationally collapsing (i.e. $\text{div } \mathbf{v} < 0$). We also adopt the Kennicutt–Schmidt law for the star formation rate (SFR), which is described as $\text{SFR} \propto \rho_g^{\alpha_{sf}}$ (Kennicutt 1998), where α_{sf} is the power-law slope with a reasonable value of $\alpha_{sf} = 1.5$ been adopted for all models.

Each SN is assumed to eject the feedback energy (E_{sn}) of 10^{51} erg and 90 per cent and 10 per cent of E_{sn} are used for the increase of thermal energy (‘thermal feedback’) and random motion (‘kinematic feedback’), respectively. The thermal energy is used for the ‘adiabatic expansion phase’, where each SN can remain adiabatic for a time-scale of t_{adi} . This time-scale is set to be 10^6 yr. A canonical stellar IMF proposed by Kroupa (2001), which has three different slopes at different mass ranges is adopted and the IMF is assumed to be fixed at the canonical one. The chemical evolution, SN feedback effects, and dust formation and evolution are therefore determined by the fixed IMF.

2.5 Metal and dust enrichment

The model for chemical enrichment and dust evolution is discussed in detail by B13. Therefore, we only briefly describe the model here. The present chemodynamical simulations include chemical enrichment through star formation and metal ejection from SN Ia, II, and asymptotic giant branch (AGB) stars self-consistently. Therefore, they can predict the time evolution of the 11 chemical elements of H, He, C, N, O, Fe, Mg, Ca, Si, S, and Ba for each model. The time delay between the epoch of star formation and those of supernova explosions and commencement of AGB phases (i.e. non-instantaneous recycling of chemical elements) is also fully considered. We adopt the nucleosynthesis yields of SNe II and Ia from Tsujimoto et al. (1995) and AGB stars from van den Hoek & Groenewegen (1997b) in order to estimate chemical yields in the present study.

The dust model adopted in the present study is the same as those in B13. The total mass of j th component ($j = \text{C, O, Mg, Si, S, Ca, and Fe}$) of dust from k th type of stars ($k = \text{I, II, and AGB for SNe Ia, SNe II, and AGB stars, respectively}$) are derived based on the methods described in B13. Dust can grow through accretion of existing metals on to dust grains with a time-scale of τ_{acc} . Dust grains can be destroyed, though supernova blast waves

Figure 2. Time evolution of the DMSH orbit, the pericenter passage can be seen to occur around ~ 0.15 Gyr. The distance of the pericenter for the orbit is at 35 kpc, which means it will only interact with the gas disc, and not the stellar disc of the host galaxy.

in the ISM of galaxies and the destruction process is parametrized by the destruction time-scale (τ_{dest}). We consider the models with $\tau_{acc} = 0.25$ Gyr and $\tau_{dest} = 0.5$ Gyr, and the reason for this selection is discussed in B13.

2.6 DMSH orbit

The orbit of an interacting pair of a disc galaxy and its DMSH is set to be initially in the x – y plane in all of the simulations. The initial distance between the centre of mass of the two (R_i), the pericenter distance (R_p), and the orbital eccentricity (e_o) can control the orbital evolution of the DMSH, and they are considered to be free parameters. The spin of the disc galaxy is specified by two angles, θ and ϕ (in units of degrees), where θ is the angle between the z -axis and the vector of the angular momentum of a disc and ϕ is the azimuthal angle measured from x -axis to the projection of the angular momentum vector of a disc on to x – y plane. The orbit of the DMSH is also specified as either prograde or retrograde, with a prograde orbit having $\theta = 45$ and retrograde orbit having $\theta = 225$ deg.

The most important parameter in the present investigation is the mass ratio of a DMSH to its host disc galaxy:

$$m_2 = \frac{M_{h,sub}}{M_h}. \quad (4)$$

We investigate the models with different m_2 so that we can better understand the roles of the dark impact on the outer cold gas of disc galaxies. We mainly investigate the models with the following orbital configuration: $\theta = 45$ and $\phi = 30$, $R_i = 52.5$ kpc, $R_p = 21$ kpc, and $e = 0.8$. It should be noted here that dynamical friction of a DMSH against the DM halo of its host galaxy can change R_p from its initial setting. Fig. 2 shows the evolution of the DMSH orbit with reference to the galaxy, the orbit of the DMSH only interacts with the gas disc (R_g) of the galaxy and not the stellar disc (R_s), so for considerations of gas kinematic and density structures we analyse the 2D gas maps of the galaxy. The pericenter passage of the DMSH occurs at $T = 0.15$ Gyr.

2.7 2D Kinematic and density maps

The details of a way to produce such 2D maps are given in Bekki 2018, we briefly describe it here. The 2D kinematic map of gas is a plot of the average line of sight (LOS) velocity of gas V_{LOS} for

each mesh, using all gas particles in the simulation. We use 50×50 meshes for the visualization, which for a standard MW-type galaxy ($M_h = 10^{12} M_\odot$), ranges from -25 to 25 kpc, and for dwarf-sized galaxies ($M_h = 10^{10} M_\odot$) it spans from -5 to 5 kpc. The average velocity for a mesh with N total particles, and the i th particle having a z -velocity $v_{z,i}$, can be calculated using equation (5). The kinematic gas plots are created with respect to the x - y plane.

$$V_{\text{LOS}} = \sum_i^N \frac{1}{N} V_{z,i} \quad (5)$$

The 2D density map of gas shows the log density of gas Σ_g for each mesh, and we calculated the log density for each mesh using equation (6). M_i represents the mass of the i th particle, we used all gas particles in the simulation in this calculation. To make the density map easier to read we assign the cells with no particles a log density 0.2 below the minimum log density. For a full-scale galaxy, each mesh represents 1 kpc^2 , so ΔR^2 can be set to 1; however, for the smaller dwarf galaxies, each mesh is 0.2 kpc in width so we need to change the ΔR^2 accordingly. The gas density plots are created with respect to the x - y plane.

$$\Sigma_g = \log \left(\sum_i^N \frac{M_i}{\Delta R^2} \right). \quad (6)$$

2.8 Quantification of kinematic and density maps

To quantify the impact of the DMSH on the outer gas discs of galaxies, we use a parameter labelled the F -parameter, which is defined as shown in equations (7) and (8). The F -parameter is calculated for both the 2D kinematic gas map (F_{kin}) and the 2D gas density map (F_{dense}). This parameter aims to quantify the disturbance the DMSH impact has on the galaxy. F_{kin} is the summation across all meshes (i, j) of the absolute difference between, the total z -velocity at time T , and time $T = 0$, and is normalized by the total z -velocity at $T = 0$. F_{dense} is the summation across the meshes (i, j) of the absolute difference between, the total mass of gas at time T and at time $T = 0$, and is normalized by the total mass of gas at $T = 0$. The F -parameters aim to quantitatively capture the perturbations in the velocity and density fields, as the DMSH impacts the galaxy:

$$F_{\text{dense}} = \sum_i \sum_j \frac{|\Sigma_{g,ij}(T) - \Sigma_{g,ij}(T=0)|}{|\Sigma_{g,ij}(T=0)|}, \quad (7)$$

$$F_{\text{kin}} = \sum_i \sum_j \frac{|V_{ij}(T) - V_{ij}(T=0)|}{|V_{ij}(T=0)|}. \quad (8)$$

These F -parameter calculations are carried out on both the 2D kinematic gas maps and 2D density gas maps. $\Sigma_{g,ij}$ refers to the total mass of gas for the (i,j) th mesh, and V_{ij} refers to the total z -velocity for the (i,j) th mesh. Total velocity refers to the summation of all of the particle velocities within the mesh, this results in the total net velocity for any given mesh.

2.9 Automatic classification model

To automatically quantify the kinematic impact DMSHs have on the outer portions of the galactic disc, we use a DL convolution neural network. DL is part of the broader family of machine learning methods, and it excels at image classification (LeCun, Bengio & Hinton 2015; Goodfellow, Bengio & Courville 2016). We aim to exploit the speciality of convolution neural networks (CNN) to help

with the classification of dark impact galaxies. DMSH impacts are sometimes so minor that, to the human eye, there is no noticeable difference in the 2D kinematic gas map of the galactic disc. Using DL we aim to classify even faintly impacted galaxies as either isolated or interacting.

A number of authors have used DL approaches for optical galaxy classification, and transient detection on SDSS data (e.g. Blanton et al. 2017; Domínguez Sánchez et al. 2018; Soo et al. 2018; Zhang, Zhang & Zhao 2018). Upcoming surveys such as WALLABY (Koribalski et al. 2009), MIGHTEE (Jarvis et al. 2017), and LSST (O’Mullane & LSST Data Management Team 2018) would greatly benefit from automatic classification algorithms, as they have proved powerful tools for processing large volumes of galaxy data.

We used supervised DL for the classification process. Supervised DL is a technique that has two phases: the training phase and the testing phase. During the ‘training phase’, we provide galaxy images (known as the training set), and their corresponding outcomes (1 if interacting and 0 if isolated) to the model, which then trains the model parameters. The ‘testing phase’ part of the process involves using a different set of galaxy images (known as the test set), which the DL system has not been trained with. This testing phase will test how well the model correctly classifies images it has not seen as a percentage of the testing data. After completing many epochs (iterations) of the training and testing, the algorithm becomes progressively more accurate as it learns and improves. After a certain number of epochs, however, the model reaches an accuracy plateau and we get diminishing returns.

DL algorithms make use of multiple neural network layers to allow for better recognition of subtle features on the object image as shown in Fig. 3. The model employed for the classification involves two convolution layers followed by max-pooling and dense layers, which can be simplistically represented as in Fig. 3. These layers in the DL model are called ‘hidden layers’.

The implementation of the DL model was using the python toolkit, keras (Chollet et al. 2015). Keras is a high-level application programme interface for tensorflow (Abadi et al. 2016). After importing and randomly sorting the data into training and testing data, the DL model was constructed, compiled and executed using keras, details of the model are shown in the results section. For our DL model, we use a binary cross entropy loss function and the Adam optimizer (Kingma & Ba 2014). The Adam optimizer is an optimization algorithm used to update the network weights iteratively during the training phase. The loss function is used to determine the error for a particular prediction. The binary cross entropy loss function was selected for this application, because we are dealing with only two classifications for the simulated galaxy images.

2.10 Parameter study

Using multiple simulations, we aim to quantify the impact of the DMSH on the extended discs of galaxies. We use a range of different galaxy models with different parameters to understand the impact of the DMSH on a variety of extended gas discs. These parameters include the galaxy mass (ranging from MW-type galaxies to dwarf galaxies), galaxy inclination, DMSH mass ratio, and the gas richness of the corresponding DMSH. Table 3 outlines the different galaxies models used to test the effects of dark impact. DMSHs without gas are termed gasless DMSHs, and the DMSHs with a small fraction of gas are termed gas-rich DMSHs.

Figure 3. Illustration of the DL model, the feature breakdown of the model. The major constituents are the convolution and max-pooling layers.

Table 3. Parameter values for the representative models.

Model name ⁶	$M_{\text{dm}} (M_{\odot})$	f_g	m_2 ⁷	Galaxy type	Gas richness of DMSH	Orbit ⁸	Inclination angles ⁹	Pericenter passage ¹⁰
M1	10^{12}	0.1	0.01	Fiducial	Gasless	P	45,30,0,0	1.2
M2	10^{12}	0.1	0.01	Fiducial	Gas rich	P	45,30,0,0	0.8
M3	10^{12}	0.1	0	Fiducial	No DMSH	P	45,30,0,0	1.2
M4	10^{12}	0.1	0.001	MW type	Gasless	P	45,30,0,0	1.2
M5	10^{12}	0.1	0.003	MW type	Gasless	P	45,30,0,0	1.2
M6	10^{12}	0.1	0.03	MW type	Gasless	P	45,30,0,0	1.2
M7	10^{11}	0.3	0.001	LMC	Gasless	P	45,30,0,0	1.2
M8	10^{12}	0.1	0.01	MW type	Gasless	P	45,30,0,0	1.8
M9	10^{12}	0.1	0.01	MW type	Gasless	P	60,30,0,0	1.2
M10	10^{12}	0.1	0.01	MW type	Gasless	P	45,30,30,0	1.2
M11	10^{10}	0.5	0.03	Dwarf	Gas rich	R	225,30,0,0	0.3
M12	10^{10}	0.5	0.03	Dwarf	Gasless	R	225,30,0,0	0.3
M13	10^{12}	0.1	0.01	MW type	Gas rich	R	225,30,0,0	0.3
M14	10^{12}	0.1	0.003	MW type	Gas rich	R	225,30,0,0	0.3
M15	10^{12}	0.1	0.001	MW type	Gas rich	R	225,30,0,0	0.3
M16	10^{12}	0.1	0.0003	MW type	Gas rich	R	225,30,0,0	0.3

3 RESULTS

3.1 Fiducial model

Fig. 4 illustrates how the dynamical impact of a DMSH on the outer gas disc of galaxies can influence the 2D kinematic and gas density maps over ~ 0.6 Gyr for the fiducial model M1. For the first 0.14 Gyr, the kinematics seem relatively unchanged, and then the initially straight zero-velocity curve (indicated by the white meshes in Fig. 4) starts to kink at $T = 0.21$ Gyr, as indicated by the circle. This impact is manifested in the 2D kinematic gas map ~ 0.07 Gyr after the pericenter passage of the DMSH. We can see this feature still exists at 0.28 Gyr, however, does not last long, and quickly disappears after the DMSH has traversed away from the galaxy. After $T = 0.35$ Gyr, no clear evidence remains of the DMSH impact on the 2D kinematic gas map.

The 2D gas density map does not show the evidence of the DMSH impact as clearly as the 2D kinematic gas map; however, there are some interesting features that form in the density map, as a result of the DMSH impact. First, we can see that at 0.21 Gyr (same time as the kink in the kinematic map forms), there is a slight kink in the density map, as shown by the red circle in Fig. 4 on the right. This feature then evolves over time, and causes a density spiral wave to propagate around the galaxies outer gas disc. At larger times ~ 0.56 Gyr, we can see the formation of a large spiral with significantly lower gas density than the surrounding, this remaining feature is present well after the pericenter passage of the DMSH, unlike the feature in the 2D kinematic gas map.

We investigated the model M2, in which the DMSH initially contains a small fraction of gas. This model will help understand how the hydrodynamical interactions between the gas in the DMSH, and

Figure 4. 2D kinematic gas map of M1 (left), and 2D gas density map of M1 (right), for different time-steps, where time is shown in the upper left corner. The circle highlights the feature caused by DMSH impact, it kinks both the 2D kinematic gas map and 2D density gas map. The bar measures 5 kpc.

the MW-type galaxy, can influence the outer gas disc of the host galaxy. Fig. 5 shows a comparison of the 2D kinematic gas maps of models M2 and M3 (isolated fiducial model). The development of the kink in the zero-velocity curve is indicated by the circle starting at $T = 0.21$ Gyr for model M2, which corresponds to the tidal disturbance caused by the DMSH, this feature is lacking in M3, which is expected for an isolated galaxy with no tidal interaction. Another feature of note is the formation of a wake in the 2D kinematic gas map, as indicated by the box in Fig. 5, which forms in the gas-rich model M2. This feature is much less pronounced in the gasless model M1 and seems to be amplified by gas-rich DMSH impact. The development of this feature is unique to gas-rich DMSH impact and is caused by the hydrodynamical push of the gas in the DMSH on the gas in the outer disc of the host galaxy.

To further quantify the interaction of the DMSH with the outer gas discs of galaxies, we analyse the evolution of the F -parameter. Figs 6 and 7 show the evolution of the F_{dense} and F_{kin} parameters, respectively, for the fiducial models, as is expected the interaction galaxies M1 and M2 have a spike in the F -parameter, whereas the isolated galaxy M3 remains relatively flat. The F_{dense} parameter increases by a factor of ~ 2.2 for model M2 with reference to the isolated model, whereas model M1 has a less marked spike at ~ 1.6 times the isolated benchmark, at the maximum point $T = 0.35$ Gyr. The reason for this is, the F_{dense} parameter (hence the 2D gas density map) is affected by two major dynamical processes, through tidal interaction, and through hydrodynamical (gas–gas) interactions. The larger spike in the F_{dense} parameter for the gas-rich model can be attributed to the fact that a gas-rich DMSH impact causes greater disturbance in the density of the outer gas disc of the galaxy, because of the gas–gas interactions between the DMSH gas and the outer gas disc. This can result in significant displacement of the gas particles in the gas disc of the galaxy, and hence can create a much more pronounced impact on the 2D gas density map (and so F_{dense}) of the galaxy for gas-rich DMSH impact, when compared to the purely tidal impact of the gasless DMSH.

For the F_{kin} parameter, we again see that the gas-rich DMSH model M2 increases much more than the gasless model M1. This can again be attributed to the fact that the gas-rich DMSH impacts

the extended gas disc through two physical mechanisms, tidal and hydrodynamical, whereas the gasless DMSH can only influence the disc through purely tidal interactions. This disparity in the gas-rich influence is more striking in the F_{kin} parameter than the F_{dense} parameter.

The pericenter passage of the DMSH as shown in Fig. 2 is at ~ 0.15 Gyr, and the first sign of the tidal impact on the 2D kinematic gas map, as highlighted by the circle in Figs 4 and 5, is at $T = 0.21$ Gyr. This means it takes ~ 0.06 Gyr for the effect of the DMSH impact to become visible on the 2D kinematic gas maps. This delayed visible reaction in the 2D kinematic gas map is because the tidal disturbance will be more pronounced once the DMSH has passed through and is moving away from the galaxy. The tidal disturbance is greater when the DMSH is initially moving away from the galaxy, and gravitationally pulling the gas particles along, causing the kink features in the zero-velocity curve.

Considering the evolution of the F -parameter the first peak in the F_{dense} parameter occurs at ~ 0.35 Gyr, which is ~ 0.2 Gyr after the pericenter passage of the DMSH. This indicates that the peak in the F_{dense} parameter occurs after one full rotation of the galaxy (0.2 Gyr) the dynamical time of the galaxy. This result was also noticed by Chakrabarti & Blitz (2009), where it was shown that the maximum effect on the 2D surface density maps is after one dynamical time of the pericenter passage.

3.2 Parameter dependence

To expand on the fiducial model, and study the complete extent of DMSH impact, we consider multiple changeable parameters, such as galaxy mass, galaxy inclination, mass ratio of the DMSH (m_2), and the gas richness of the companion DMSH. Each of these parameters affects how the DMSH interacts with the galaxy, and again, we use both 2D kinematic and gas density maps to study the effect of the DMSH impact on the gas discs of galaxies with different parameters. Fig. 8 shows the 2D kinematic gas maps for a variety of different models, as described in Table 3. We observe that the DMSH impacts the 2D kinematic gas maps of these models in different ways. Within this plot are a range of DMSH mass ratios,

Figure 5. Evolution of the 2D kinematic map of gas for M2 (left), and M3 (right), with time shown on the upper left corner. There is a visible kink in 2D kinematic gas map (shown by the circle) for M2, which is caused by tidal disturbance of the DMSH impact. The box shows the formation of a wake in the 2D kinematic gas map of M2, not seen in M1, at $T = 0.56$ Gyr. This feature is unique to M2, with the gas-rich DMSH impact. M3 remains undisturbed throughout the evolution, as we expect for an isolated galaxy. The bar measures 5kpc.

Figure 6. Evolution of the F_{dense} parameter for models M1 (dotted), M2 (dashed), and M3 (solid). M1 and M2 show characteristic peaks due to their interaction with a DMSH, whereas M3 lacks this feature as it is isolated. M2 has a more pronounced spike than M1, this is because M2 has a gas-rich DMSH, which can influence the 2D gas density map via tidal and hydrodynamical interactions, as opposed to the gasless DMSH in M1, which can only tidally affect the outer gas disc.

Figure 7. Evolution of the F_{kin} parameter for models M1 (dotted), M2 (dashed), and M3 (solid). Again M1 and M2 show marked increases due to their interaction with a DMSH, whereas M3 lacks this feature as it is isolated. M2 increases more than M1 because of the gas-rich DMSH, this causes a more pronounced impact on the extended gas disc and hence leads to a larger impact on the F_{kin} parameter.

3.2.1 Mass ratio of DMSH

To investigate how different DMSH mass ratio affects the outer gas discs of galaxies, multiple simulations were run with different DMSH mass ratios from $m_2 = 0.001$ to 0.03. We can then study the 2D kinematic gas map of the galaxies at the point where their F_{kin} parameter is at its highest, or when the greatest disturbance is seen, this way we can compare the effect of the different DMSH mass ratios.

Fig. 9 shows the 2D kinematic gas map of four galaxies with progressively higher DMSH mass ratios. The kinematic impact on the galaxies is evidently increasing as the DMSH mass ratio increases, this result is seen through progressively larger kinks in the zero-

galaxy inclinations, and galaxy masses. We discuss in detail the dependence of the structure formation with regards to the mass ratio of the DMSH and the gas richness of the DMSH.

Galaxy inclination influences the detail of the 2D kinematics of the gas disc such as kinks and warps of the zero-velocity curve. For the inclined galaxies, however, the observations are a lot fainter and the kink in the kinematic curve is not as pronounced as it is for the face on fiducial model. This can be seen through the inclined galaxy M9, which is inclined in the θ -direction. There is a small signature of the DMSH impact; however, it is not as clear as in M1.

Figure 8. 2D kinematic gas distributions of galaxies with different parameters, with the model numbers in the upper left. These plots are taken for the time-step, where F_{kin} (kinematic image disturbance) is the largest. The bar measures 5 kpc.

Figure 9. 2D kinematic gas distributions of four galaxies, with the mass ratios of DMSHs (shown in the upper left), varying from $m_2 = 0.001$ to 0.03. The higher mass ratio impacts cause significantly larger disturbances. The bar measures 5 kpc.

velocity curves of the galaxies. The impact is very pronounced for $m_2 = 0.01$ and 0.03, where the latter's disc is significantly morphed at the impact site. In comparison, the impact for $m_2 = 0.001$ is barely visible in the 2D kinematic gas map.

Table 5 shows a comparison of the maximum F_{kin} and F_{dense} values for the different DMSH mass ratios. There is a linear increase in both F_{kin} and F_{dense} with the increasing mass ratio, which is intuitive as you expect the increasingly larger DMSH mass ratios to have increasingly larger impacts on the galaxies 2D kinematic maps. A complete comparison of the maximum F_{kin} and F_{dense} values is shown in Table C1 in Appendix C. Equation (9) shows the line of regression for the maximum F_{kin} value as a function of the DMSH mass ratio (m_2):

$$F_{\text{kin}} = 1.52 \times 10^5 m_2 - 2.50 \times 10^2. \quad (9)$$

Table 5. F_{kin} and F_{dense} maximum values for models with different mass ratio DMSHs (m_2). The F_{kin} and F_{dense} parameters aim to numerically quantify the impact the DMSH has on the extended gas disc of the galaxy. The larger the F_{dense} and F_{kin} , the greater the disturbance caused on the density, and kinematic plots, respectively. The table illustrates that with larger mass ratio DMSHs, we have increasingly larger maximum values of the F -parameters.

Model name	m_2	Max F_{kin}	Max F_{dense}
M4	0.001	9.30×10^1	3.04×10^2
M5	0.003	2.07×10^2	3.32×10^2
M1	0.01	9.92×10^2	4.62×10^2
M6	0.03	4.40×10^3	7.43×10^2

Figure 10. 2D kinematic gas distribution for M11 (left), and M12 (right), at the final time-step $T = 0.084$ Gyr. The circle indicates the signature of a DMSH impacts tidal features, and the box highlights the structures formed in the gas-rich impact M11 alone. The bar measures 1 kpc.

Equation (10) shows the regression line for the maximum F_{dense} value as a function of the DMSH mass ratio (m_2):

$$F_{\text{dense}} = 1.51 \times 10^4 m_2 + 2.94 \times 10^2. \quad (10)$$

3.2.2 Gas richness of companion DMSH

The 2D kinematic gas map of model M2 in Fig. 5 shows interesting structure formation in the outer gas disc, this was highlighted by the box. This feature was unique to the gas-rich DMSH impact. To study the dependence of the structure formation on the gas richness of the DMSH, we studied two simulated dwarf galaxies in more detail. Model M11 (gas-rich DMSH) and M12 (gasless DMSH) are both interacting dwarf galaxies with a DMSH mass ratio of $m_2 = 0.03$. A larger mass ratio was used to get a more pronounced response in the galaxy.

Fig. 10 shows the 2D kinematic gas map of both of the dwarf galaxies at their final time-step $T = 0.084$ Gyr. We observe that for both of the models, there is the signature kinking of the zero-velocity curve on the 2D kinematic gas map, which can be attributed to the tidal disturbance caused by the DMSH impact, this feature is shown circled. There also is a region in M11 where there is fragmented gas ‘flung’ out of the galaxy, this feature is not seen in M12 and is unique to the gas-rich DMSH impact. This feature can be attributed to the hydrodynamical interactions caused by the gas-rich DMSH on the outer gas disc of the galaxy.

Fig. 11 shows the 2D gas density distribution of M11 and M12 that displays some very interesting structure formation. On the gasless model M12, there are no major features visible and the 2D gas density map seems relatively undisturbed. For the gas-rich model, the gas which is ‘flung’ out of the galaxy can be seen again in the 2D gas density map, as indicated by the box in Fig. 11. There is also a large hole that forms in the outer gas disc of the galaxy and

Figure 11. 2D gas density maps for M11 (left), and M12 (right), at the final time-step $T = 0.084$ Gyr. Model M11 has a hole in the gas disc, as well as disturbance (gas ‘flung’) outside the galaxy in the 2D gas density map, similar to the feature seen in the 2D kinematic gas map. Model M12 has neither present in the 2D gas density map. The bar measures 1 kpc.

corresponds to the passage of the DMSH. This hole is unique to the gas-rich DMSH impact and is caused because of the hydrodynamical push exerted by the gas in the DMSH on the gas in the outer gas disc of the galaxy; hence, for a gasless model because of the lack of gas in the DMSH, there is no visible hole formed in the outer gas disc. To confirm this, hole feature can be created in a full-scale MW-type galaxy, model M13 was investigated, which is MW-type galaxy and has a gas-rich DMSH impact with a mass ratio of $m_2 = 0.01$. Results of model M13 are discussed in Appendix A.

The evolution of the hole in the outer gas disc and fragmented gas features can be analysed using time-stepped 2D gas density maps for model M11 as shown in Fig. A4. Further discussion of this figure is presented in Appendix A.

DMSH impact affects the 2D kinematic gas map of both the gas-rich and gasless DMSHs, as is seen in the figures presented. This is because tidal disturbances cause the kinematic features and are present in both of the DMSH impacts. Using this, we conclude that the kinematic features, such as the kinking of the 2D kinematic gas distribution, present in the interacting galaxies, are a feature of purely tidal interactions between the DMSH and the galaxy outer gas disc. Other features in the kinematic gas map, such as the fragmented gas, are caused only for gas-rich DMSH impact. The features caused in the 2D gas density maps, such as the hole in the gas disc and the ‘flung’ out gas, are only present in the gas-rich DMSH with a retrograde orbit. This is because the density map features are a product of the gas–gas interactions between DMSH and the outer gas disc of the galaxy. This interaction causes the prominent hole in the outer gas discs of the galaxies. This hole is an important feature from an observational standpoint, as many surveys can produce gas density maps for galaxies and this is where the impact of the gas-rich DMSH can manifest itself very clearly.

4 DISCUSSION

4.1 Deep learning classification results

As an extension to the study, we use DL to automatically classify 2D kinematic images of galaxies as either isolated or interacting. DL was chosen for its speciality in image classification through the use of convolutional neural network layers. To implement the DL model, we use a PYTHON-based library called keras (Chollet et al. 2015). Keras is a user-friendly tool that easily implements DL layers such as convolution and max-pooling. Using keras, we were able to quickly build a DL model with multiple layers as described in Table 4.

The testing accuracy for the model was ~ 94 per cent, testing accuracy refers to the percentage of correct classifications the model makes from the testing data. An accuracy of ~ 94 per cent is good; however, for very large galaxy surveys, this could result in a lot of incorrect classifications that would need to be otherwise tested. Appendix B details further plots describing the evolution of the model loss and accuracy as well as analysis on the inner working of the convolution filters.

To improve the accuracy, a more sophisticated DL model could be developed using more layers and training data. For the current model, we used 4800 images for training and 1200 for testing, these images were created from five different simulated galaxies at a variety of time-steps. As part of the study, we also prototyped an ensemble DL model that added a histogram of oriented gradients (Dalal & Triggs 2005) of the 2D kinematic gas maps. This increases the accuracy of the classification to ~ 96 per cent. Other computer vision techniques could be applied and integrated to the model. This will be described in future papers.

4.2 Observability of dark impact on the outer gas discs of galaxies

It is possible that such subtle, yet characteristic signatures of H I kinematics (and density maps), can be automatically identified in a large H I survey. WALLABY (Koribalski et al. 2009) is the ASKAP H I all-sky survey, which will have a spatial resolution of 30 arcsec. This translates to a resolution of 3 kpc at a distance of 20 Mpc and 0.3 kpc at 2 Mpc, the H I holes from the simulations are close to ~ 1 kpc in width for dwarf galaxies, shown in Fig. 11 and even larger ~ 4 kpc for MW-type galaxies, shown in Fig. A1. The H I hole also seems to be a feature in the dwarf galaxy for ~ 0.04 Gyr; however for a MW-type galaxy, this hole is taken in by the galaxy rotation and is visible for ~ 0.21 Gyr.

So from the survey of 600 000 galaxies, we can look to detect DMSH impact for galaxies within 6 Mpc. The WALLABY (Koribalski et al. 2009) project produces H I emission data, and so we can produce 2D gas density plots for the galaxies and can look to observe the signature H I hole in the galaxy, as well as traces of fragments outside the galaxy. The time-scale of the H I hole is smaller for dwarf galaxies and larger for MW-type galaxies and hence we are more likely to observe DMSH impact in MW-type galaxies.

A comparison between the simulated image, and observation image of DMSH impact is shown in Fig. 12. The simulated image as discussed shows the 2D gas density distribution in the galaxy. The observational image, taken from Wagner-Kaiser et al. (2014), is of dwarf galaxy NGC 247, and shows the H α emission in the galaxy. The H α emission shows signatures of gas that is ionized by young OB stars. As we can see both of the images show similar features, such as the void in the gas distribution as well as some fragmentation out of the galaxy that is shown by the box. The lack of H α emission in the observation image suggests a lack of recent star formation in that area. From the understanding of the simulation, this could be due to lower gas density in the area, which has been impacted by a gas-rich DMSH. This void and signs of gas fragments outside the galaxy suggest that NGC 247 may have been impacted by a gas-rich DMSH. The void in the galaxy, however, does not appear to be as large as the void shown in the simulation plot, this could point to impact by a smaller mass ratio DMSH.

An observational study by Ryder et al. (1995) on the barred spiral galaxy NGC 1313, with a H I disc spanning (24×13 kpc), has shown ‘supershells’ forming in the H I disc of the galaxy. These

Table 4. Description of the DL model we apply in the automatic classification of the 2D kinematic gas maps of galaxies. The parameters of model layers were tweaked within keras to achieve greater accuracies. For the table, filter size refers to the size of the convolution and max-pooling filters, used to run over the image. The activation for each of the layers is the non-linearity function employed within the model. ReLU (rectifier linear unit) and sigmoid are the two activation functions used in this model.

Layer name	Number of features	Filter size	Activation	Strides
Convolution layer	15	(7,7)	ReLU	–
Max-pooling layer	–	(2,2)	–	1
Convolution layer	15	(2,2)	ReLU	–
Max-pooling layer	–	(2,2)	–	1
Dropout (0.4)	–	–	–	–
Flatten	–	–	–	–
Dense	128	–	Sigmoid	–
Dense	50	–	Sigmoid	–
Dense	2	–	Sigmoid	–

Figure 12. Comparison between observational results (left) (Wagner-Kaiser et al. 2014) and the simulated model M11 (right). The circle highlights the void in the galaxies, and the box shows the gas fragments, possibly resulting from the hydrodynamical push exerted by the DMSH gas on the galaxies outer gas disc. Left image is reproduced (adapted from fig. 9 of Wagner-Kaiser et al. 2014) with permission from Oxford University Press on behalf of the Royal Astronomical Society (RAS).

supershells show drops in the H I column density ~ 10 per cent lower than the average value at that radius. The shell is shown to have a diameter of ~ 4.3 kpc. This suggests that the hole is fairly large, from the simulated results we observe a spiral galaxy, with a gas disc radius of 35 kpc, exhibiting a H I hole of ~ 4 kpc, for a gas-rich DMSH impact, with mass ratio of $m_2 = 0.003$, as shown in Fig. A2. This study postulates that to create such a large hole in the H I disc of the galaxy, 10^3 supernovae in 10^7 yr are required; however, they have not detected any optical, radio, or x-ray remnants of the hypothetical starburst. This observational results points to the possibility that this supershell was created by DMSH impact on the galaxy.

Another mention of H I supershells is by Rand & van der Hulst (1993), where an observational study found the existence of two supershells in the H I disc of the edge-on galaxy NGC 4631. These two supershells have diameters 1.8 and 3 kpc. In the study, they discuss the possibility of supernova and stellar winds creating such supershells; however, they consider that a more attractive method of explanation is collision of small or massive gas clouds with the disc of the galaxy. The possibility of collision with an external gas cloud has not been supported by observation, because there were no observational signatures of such an interaction. This could point

to the possibility of the H I supershells forming through multiple DMSHs impacts.

4.3 Comparison of results with other DMSH impact studies

This paper shows how DMSH impact on outer gas discs of galaxies can influence the formation of features in both the 2D gas kinematics and gas density maps of galaxies. The study by Kannan et al. (2012) also studied the influence of DMSH impact on the outer gas discs of galaxies and found that DMSHs with a small fraction of gas can induce the formation of H I holes in the disc of the galaxy. This was also noticed in the results presented by this study; however unlike Kannan et al. (2012), we test DMSH impact for a variety of DMSH mass ratios to identify whether the impact is visible or not, and analyse both the 2D kinematic and density maps of gas as opposed to just the 2D density maps of gas.

Chakrabarti & Blitz (2009) studied the perturbations of H I in the MW to infer the existence of a DMSH that dynamically impacted the MW. The analysis presented in the study focused on the Fourier modes of the H I gas, the surface density maps of gas, and techniques to determine the mass of the dark perturber that

caused the observed disturbances in the H I map of the MW. Similar to the works presented in this paper, it was found that DMSH impact causes spiral waves to propagate in the gas surface density maps, and more notably the maximum effect of this is noticed after one dynamical time, similar to what was observed in this study. However, Chakrabarti & Blitz (2009) focused solely on the surface density maps of gas and not the kinematic maps of gas. Also, there was no parameter study conducted, as the aim of the paper was to study the specific circumstance that induced features similar to the observation in the MW.

4.4 Future work: interaction between galactic gas discs and multiple DMSHs

So far we have discussed the physical properties of gaseous discs of galaxies being dynamically influenced by just single DMSH. However, as there are multiple dark satellites surrounding galaxies, there could be multiple interactions with the galactic disc that could give rise to interesting features. With multiple dark impacts, there could be possibly greater tidal disturbance of the disc, and possibly even more violent interactions with the extended gas disc of galaxies.

This can be studied through hydrodynamical simulations, with numerous DMSH of different sizes, interacting with the outer gas disc of the galaxy. With numerous impacts, we can expect that the DMSHs may also self-interact causing interesting features through greater tidal disturbance of the outer gas disc of the galaxy. Also with more frequent and numerous impacts, we could maybe see the evolution of an H I hole without the need for gas-rich DMSH impact; this could be due to two minor gasless impacts causing sufficient tidal disturbance and leading to the tidal stripping of the gas, as opposed to a hydrodynamical push.

5 CONCLUSIONS

Using hydrodynamical simulations, we have investigated DMSH impacts on the outer H I discs of galaxies. We have done this by running various simulations with different parameters, such as mass ratio, inclination, and gas richness of the DMSH. To analyse the results, we used a combination of 2D kinematic and gas density maps along with a numerical F -parameter. From this, we have determined a few key markers for different DMSH impacts, which can be summarized as follows:

(i) All DMSH impacts cause a perturbation in the 2D kinematic gas map of galaxies. This feature is due to the tidal interaction between the outer gas disc of the galaxy and the DMSH, which causes a bend in the 2D kinematic gas map as shown in Fig. 4. The bend is more pronounced for larger mass ratio DMSHs, as is shown in Fig. 9, and is unidentifiable for $m_2 < 0.003$.

(ii) Impact caused by the DMSH creates a spike in the F -parameter for both F_{dense} and F_{kin} . The F_{dense} parameter then resumes back down, whereas the F_{kin} parameter does not. A possible reason for this is that the density can ‘settle’ down, because gravitational forces will gravitate back rogue particles, whereas for kinematics, there are no such forces that will restore the particles. Also, gas-rich DMSH impact has a larger influence on the F_{kin} , and to a lesser extent F_{dense} when compared to the gasless DMSH impact. This is because the gas-rich impact influences the outer gas disc through both tidal interactions and hydrodynamical interactions, whereas the gasless DMSH impact only influences through tidal interactions.

(iii) Gas-rich DMSH impacts that have retrograde orbits cause a hole in the H I disc of galaxies as is shown in Figs 11 and A1. This hole is a results of a hydrodynamical push exerted by the DMSH gas on the outer gas disc of the galaxy. Along with this, gas-rich models have fragments of gas outside the galaxy. These fragments are present for dwarf-sized galaxy, $M_h = 10^{10} M_\odot$, and not full-scale MW-type galaxies, $M_h = 10^{12} M_\odot$.

(iv) Another feature of note is that the stellar disc of galaxies is not influenced by DMSH impact. This can be seen through Fig. A3, where both the gas-rich and gasless DMSHs show no effect on the 2D density distribution of the stellar disc. This is an important conclusion and is of importance for observational studies that aim to find DMSH impact on galaxies.

(v) DL models for classifying kinematic images are powerful and accurate, with an accuracy of ~ 94 per cent. These models have room for improvement but show that automatic classification of DMSH impact is possible. Building a DL model will have great uses in large data set classification, this will streamline and optimize the process. Also as mentioned, some DM impacts register little effect on the 2D kinematic gas maps, accordingly DL models would be more accurate than human eye at identifying these minor impacts.

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APPENDIX A: GAS-RICH IMPACT

The model M13 is an interaction MW-type galaxy model with a retrograde, gas-rich DMSH impact. Fig. A1 shows that the hole in the 2D gas density map is also present in model M13. For this model however we cannot observe the gas which is ‘flung’ out due to the DMSH impact. It seems like the larger galaxy has the ability to quench the impact and retain the gas disc, when compared to the dwarf galaxy.

The model M13 is similar to M2, however, the formation of H I hole is only visible in M13. The reason for this is that M2 has prograde orbit, where the DMSH orbit and the galaxy rotation are in the same direction, M13 has a retrograde orbit, where the DMSH orbits opposite to the galaxy rotation. The formation of the H I hole is related to this feature of the orbit where even M11 that has the observed H I hole has a retrograde orbit. To investigate the limitation on the formation of the H I hole, we ran models M14, M15, and M16 all similar to model M13 however with progressively smaller

Figure A1. 2D gas density map for MW-type model M13, with retrograde gas-rich DMSH impact at time $T = 0.14$ Gyr. We observe the H I hole in this model as well; however, the gas features outside the galaxy are not visible. The bar measures 5 kpc.

Figure A2. 2D gas density maps for four different models with different mass ratio DMSHs (m_2) shown in the top right. This illustrates that larger mass ratio DMSHs develop increasingly larger H I holes in the outer gas disc. Mass ratio of a companion lower than $m_2 = 0.001$ result in no visible H I hole formation. The bar measures 5 kpc.

Figure A3. 2D stellar density map for M11 (left) and M12 (right) at their final time-step. The DMSH impact (both gas-rich and gasless) seems to have no effect on the distribution of stars. The bar measures 1 kpc.

DMSH mass ratios. Fig. A2 shows the dependence of the mass ratio on the formation of the H I hole, we observe that after $m_2 = 0.001$ we can no longer observe the DMSH impact on the 2D gas density map of the galaxy.

So far we have looked at the 2D kinematic and density maps of gas; however, we can extend this analysis to the 2D density map of stars for both the gas-rich and gasless DMSH impacts. Fig. A3 shows the 2D density map of stars for both M11 and M12, the stars in both models remain relatively undisturbed and seem to be uninfluenced by the DMSH impact. This is because the stars are confined in the more tightly bound stellar disc $R_s = 0.5R_g$, which the DMSH does not directly influence. From an observational standpoint, this suggests that using stellar images that rely on star emissions would prove ineffective in detecting DMSH impact because stars are less influenced by both gas-rich and gasless DMSH impacts.

Figure A4. Evolution of 2D gas density map for M11 for 0.084 Gyr. The hydrodynamical collision of the DMSH with the gas disc causes the H I hole. The disintegration of the gas-rich DMSH causes the gas-features outside the galaxy. The first sign of the hole in the gas disc is outlined by the circle at 0.042 Gyr and continues to be present till 0.084 Gyr, as it is carried away by the rotation for the galaxy. The bar measures 1 kpc.

Fig. A4 shows the time-stepped evolution of the gas-rich DMSH impact model M11. From this figure, it is evident that the formation of the H I hole can be attributed to the movement of the DMSH through the galaxy. Through tidal and hydrodynamical interactions, the DMSH is able to displace the gas particles and cause the features we see surrounding the galaxy. The gas-rich DMSH impact creates a hole in the outer gas disc because of the hydrodynamical push exerted by the gas in the DMSH on the outer gas disc of the galaxy. This causes the DMSH to fragment and disintegrate, as it passes out of the galaxy, which is what the ‘flung out’ gas features are. This density feature is not however present in the model M12 with the gasless DMSH, as there is no scope for gas–gas interactions to cause a hydrodynamical interaction and hence an H I hole and outer gas disc features.

APPENDIX B: DEEP LEARNING RESULTS

Fig. B1 shows the evolution of the model loss and model accuracy. The model loss refers to a scalar value that the model aims to minimize during the training phase, and model accuracy refers to

Figure B1. Evolution of the model accuracy (upper) during the training phase (blue) and testing phase (orange). Accuracy is the number of correct predictions for the testing and training sets of data. Evolution of model loss (lower), the loss value refers to a scalar value that the model minimizes during the training phase. The lower the loss, the closer our predictions are to the true labels. As we expect the accuracy increases and loss decreases with more epochs and both of them plateau after 8 epochs, after which we get marginal improvements in the classification.

the accuracy of the model (number of correct predictions), during the training and testing phases. Both the model loss and accuracy were defined earlier in the model section. The diagram illustrates that with increasing number of epochs the model becomes more accurate. After a while the accuracy reaches a plateau and there are diminishing return from that point on.

To better understand, this result and see how the model is able to distinguish between the interaction and isolation images, we can visualize the images the model ‘sees’. This involves visualizing the images after the two convolution and max-pooling layers have been run over them. Using this, we can get a better idea of what the DL model ‘sees’. Fig. B2 shows the images of the multiple filters that come from the original image after the convolution and max-pooling layers have been parsed. The images of the interaction model have a lot more disturbance around the galaxy, whereas the images of the isolated model show fewer structures and features around the galaxy. This is mainly where the differen-

Figure B2. Feature maps for the interacting galaxy images (left) and isolated galaxy images (right). As specified our model has 15 convolution layers, all of which after being processed, are shown above. The top left image (for both interaction and isolation) is the original kinematic image of the galaxy, and all that follow are the convolved images.

tiation between the interaction and isolation images occurs within the model.

APPENDIX C: F -PARAMETER TABLE

A complete comparison of maximum F_{dense} and F_{kin} values can be seen in Table C1. We can see that the lowest F_{kin} and F_{dense} values are for models that are either LMC-type or Dwarf-type galaxies, this is because these simulation galaxies are smaller and so have smaller values for the F -parameter. Similar to the results noticed in the fiducial model, where the gas-rich DMSH model M2 has greater F_{dense} and F_{kin} values when compared to the gasless DMSH model M1. We can see that M11 (gas-rich DMSH) has greater F_{kin} and F_{dense} values when compared to M12 (gasless DMSH). This reaffirms the result that a gas-rich DMSH impacts the galaxy through tidal interactions and hydrodynamical, hence increasing the effect on the F -parameters.

Table C1. Maximum value of F_{kin} and F_{dense} for all models in the study.

Model name	Max F_{kin}	Max F_{dense}
M1	9.92×10^2	4.62×10^2
M2	3.12×10^3	6.36×10^2
M3	7.82×10^1	3.24×10^2
M4	9.30×10^1	3.04×10^2
M5	2.07×10^2	3.32×10^2
M6	4.40×10^3	7.43×10^2
M7	5.98×10^0	5.69×10^1
M8	2.02×10^3	3.40×10^2
M9	2.84×10^3	3.74×10^2
M10	8.97×10^2	4.74×10^2
M11	7.20×10^0	1.53×10^1
M12	4.93×10^0	1.29×10^1
M13	3.83×10^2	6.29×10^2
M14	1.67×10^2	4.22×10^2
M15	1.12×10^2	3.87×10^2
M16	8.05×10^1	2.54×10^2

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