INTERACTION BETWEEN DARK MATTER SUB-HALOS AND A GALACTIC GASEOUS DISK

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ABSTRACT

We investigate the idea that the interaction of dark matter (DM) sub-halos with the gaseous disks of galaxies can be the origin for the observed holes and shells found in their neutral hydrogen (H\textsc{i}) distributions. We use high-resolution hydrodynamic simulations to show that pure DM sub-halos impacting a galactic disk are not able to produce holes; on the contrary, they result in high-density regions in the disk. However, sub-halos containing a small amount of gas (a few percent of the total DM mass of the sub-halo) are able to displace the gas in the disk and form holes and shells. The sizes and lifetimes of these holes depend on the sub-halo gas mass, density, and impact velocity. A DM sub-halo, of mass $10^8 \, M_\odot$ and a gas mass fraction of $\sim 3\%$, is able to create a kiloparsec-scale hole with a lifetime similar to those observed in nearby galaxies. We also register an increase in the star formation rate at the rim of the hole, again in agreement with observations. Even though the properties of these simulated structures resemble those found in observations, we find that the number of predicted holes (based on mass and orbital distributions of DM halos derived from cosmological N-body simulations) falls short compared to the observations. Only a handful of holes are produced per gigayear. This leads us to conclude that DM halo impact is not the major channel through which these holes are formed.

Key words: dark matter – galaxies: structure – ISM: bubbles – ISM: structure

Online-only material: color figures

1. INTRODUCTION

Holes and shells have been found in the neutral hydrogen (H\textsc{i}) distribution of many nearby galaxies such as M31 (Brinks 1981, Brinks & Bajaja 1986), M33 (Deul & den Hartog 1990), Holmberg II (Puche et al. 1992), M101 and NGC 6946 (Kamphuis & Sancisi 1993), IC 10 (Wilcots & Miller 1998), the Small Magellanic Cloud (SMC; Staveley-Smith et al. 1997), the Large Magellanic Cloud (LMC; Kim et al. 1998), and IC 2574 (Walter & Brinks 1999). These structures are typically regions of low H\textsc{i} density distributed across the entire galaxy, and come in various sizes ranging from a few 100 pc to about 1.5 kpc. Their expansion velocity sets an upper limit to their dynamical age of about 10–60 Myr (cf., Walter & Brinks 1999 for IC 2574).

The formation of H\textsc{i} holes and shells has often been ascribed to the action of stellar winds and supernova (SN) explosions occurring in OB associations and young stellar clusters (cf., Weaver et al. 1977; Tenorio-Tagle & Bodenheimer 1988; van der Hulst 1996). Based on a simple model of holes created by O and B stars, Oey & Clarke (1997) successfully predicted the observed number distribution of holes in the SMC, lending support to this hypothesis. More recently, the analysis conducted by Ott et al. (2001), Simpson et al. (2005), Weisz et al. (2009a), and Cannon et al. (2011) has shown that the stellar content of H\textsc{i} holes in Holmberg I and II and DDO 88 and 165 can release enough mechanical energy to drive the formation of holes on timescales similar to what is observed. In particular, Weisz et al. (2009a) were able to show that all the holes in Holmberg II observed with the Hubble Space Telescope contain multiple stellar populations of different ages. Warren et al. (2011) studied the H\textsc{i} holes in five dwarf galaxies (DDO 181, Holmberg I, M81 Dwarf A, Sextans A, and UGC 8508) and failed to detect a young star cluster at the center of the observed H\textsc{i} holes. They thus suggested that large holes may form due to multiple episodes of star formation (SF).

There is more observational evidence against a single burst of SF being responsible for the creation of H\textsc{i} holes. For example, no robust spatial correlation was found by Kim et al. (1999) between the distribution of the H\textsc{ii} emission and the H\textsc{i} holes in the LMC. Hatzidimitriou et al. (2005) estimated that the holes in the SMC not associated with a young star cluster are a factor of 1.5 more than those exhibiting relatively young stars at their center. In the Galaxy, the distribution of radio pulsars compared to that of holes seems to indicate that holes cannot be produced by the SN explosions of a single-age stellar population (Perna & Gaensler 2004). Pasquali et al. (2008) found that the most recent episode of SF has taken place preferentially at the rims of the H\textsc{i} holes in IC 2574, an exception made for the supergiant shell which indeed embeds a young star cluster (cf., Stewart & Walter 2000; Weisz et al. 2009b). Rhode et al. (1999) observed the H\textsc{i} holes in Holmberg II in search of the descendants (stars of spectral types B, A, and F) of those clusters whose SNe would have produced the holes. They measured an integrated light of the stars within the rim of the hole, again in agreement with observations. Even though the properties of these simulated structures resemble those found in observations, we find that the number of predicted holes (based on mass and orbital distributions of DM halos derived from cosmological N-body simulations) falls short compared to the observations. Only a handful of holes are produced per gigayear. This leads us to conclude that DM halo impact is not the major channel through which these holes are formed.

Some authors have proposed alternative formation hypotheses to the SNe origin. Efremov et al. (1998) and Loeb & Perna (1998) postulate that a high-energy gamma-ray burst (GRB) from the death of a single massive star could create kiloparsec-sized holes in the interstellar medium (ISM), thus offering an explanation for holes without a detectable underlying cluster. These authors assume that the energy from GRBs is emitted isotropically. However, GRBs release most of their energy in bidirectional beams (e.g., Blandford & Znajek 1977 mechanism), making this scenario less likely to produce large H\textsc{i} holes.
Another mechanism proposed is the infall of gas clouds (Tenorio-Tagle et al. 1987). One observational prediction of this model is a half-circle arc seen in an H\textit{i} position–velocity diagram. The half-circle arc arises from the gas being pushed to one direction, corresponding to the direction of travel of the high-velocity clouds. Some observational support for this idea is reported by Heiles (1979, 1984) who point out that the most energetic Galactic shells in their study all have half-circle arc signatures in position–velocity space (Kamphuis et al. 1991).

In this paper we investigate an alternative formation scenario, where holes and shells in extended H\textit{i} disks are the result of interaction of the gaseous disk with dark matter (DM) sub-halos. The lambda cold dark matter (ACDM) model predicts the existence of thousands of DM substructures within the DM halo of every galaxy (e.g., Springel et al. 2008 and reference therein). The majority of these sub-halos is “dark,” i.e., does not host a satellite galaxy or any visible stellar structures (e.g., Macciò et al. 2010; Font et al. 2011). If this sub-halo population is able to produce the observed holes in galactic H\textit{i} disks, like the one of IC 2574, then this might provide a new way of detecting the presence of non-luminous DM halos. For example, the number of holes could then be linked statistically to the amount of substructure in the DM distribution and thus provide a unique way to assess the nature of DM and by extension to test the ACDM model.

Perturbations on a stellar disk due to (massive) satellites have been extensively studied in recent years (e.g., Kazantzidis et al. 2008; Moster et al. 2010a and references therein), while less attention has been given to the effect of low-mass DM clumps on an extended gaseous disk, with few exceptions. Bekki & Chiba (2006) investigate how the impact of DM sub-halos orbiting a gas-rich disk galaxy embedded in a massive DM halo influences the dynamical evolution of the outer H\textit{i} gas disk of the galaxy. They show that the impact of DM sub-halos (“dark impact”) can be important for better understanding the origin of SF discovered in the extreme outer regions of disk galaxies. They also discuss the possibility that this kind of dark impact will be able to produce holes in the gas distribution. In their study they adopted a model which did not include multiple events, a live DM halo (they adopted an analytic fixed potential), cooling, and SF.

A new attempt to detect the imprint of the dark satellites in the H\textit{i} disk of the Milky Way has been recently made. In a series of papers, Chakrabarti & Blitz (2009, 2011) examine tidal interactions between perturbing dark sub-halos and the gas disk of the Milky Way using high-resolution smoothed particle hydrodynamic (SPH) simulations. They compare their numerical results to the observed H\textit{i} map of the Milky Way and find that the Fourier amplitudes of the planar disturbances are best fitted by a perturbing dark sub-halo with a mass that is one-hundredth of the Milky Way’s with a pericentric distance of 5 kpc. More recently, Chang & Chakrabarti (2011) developed a perturbative approach to study the excitation of disturbance in the extended atomic hydrogen disks of galaxies produced by passing DM sub-halos. They showed that the properties of DM sub-halos can be inferred from the profile and amplitude of the different perturbed energy modes of the disk.

Motivated by these recent studies, in this paper we use high-resolution hydrodynamic simulations to study in detail the interaction of DM sub-halos with a galactic gaseous disk. Our primary goal is to see under which conditions DM satellites are able to create holes that resemble the observed ones and whether the majority of these holes can be explained by dark satellite–disk interactions. We model our primary galaxy on the nearby dwarf galaxy IC 2574 and try to replicate its observed features in our simulations. After having described our numerical setup, we will first present results of a single satellite–disk interaction, for different satellite orbital parameters and gas content. Then we will use satellite parameters (mass, velocity, and position) directly obtained from high-resolution N-body simulations to study the frequency of DM sub-halo disk encounters. Finally, we will discuss the implications of our results.

2. NUMERICAL SIMULATIONS

We make use of the parallel TreeSPH-code GADGET-2 (Springel 2005) in this work. The code uses SPH (Gingold & Monaghan 1977; Lucy 1977; Monaghan 1992) to evolve gas using an entropy conserving scheme (Springel & Hernquist 2002). Radiative cooling is implemented for a primordial mixture of hydrogen and helium following Katz et al. (1996) and a spatially uniform time-independent local ultraviolet background in the optically thin limit (Haardt & Madau 1996) is included. The SPH properties of the gas particles are averaged over the standard GADGET-2 kernel using 64 SPH particles. Additionally, the minimum SPH smoothing length is required to be equal to the gravitational softening length in order to prevent artificial stabilization of small gas clumps at low resolution (Bate & Burkert 1997).

All simulations have been performed with a high force accuracy of $a_{\text{force}} = 0.005$ and a time integration accuracy of $\eta_{\text{acc}} = 0.02$ (for further details see Springel 2005). SF and the associated heating by SNe are modeled following the sub-resolution multiphase ISM model described by Springel & Hernquist (2003). The ISM in the model is treated as a two-phase medium with cold clouds embedded in a hot component at pressure equilibrium. Cold clouds form stars in dense ($\rho > \rho_0$) regions on a timescale chosen to match observations (Kennicutt 1998). The threshold density $\rho_0$ is determined self-consistently by demanding that the equation of state (EOS) is continuous at the onset of SF. We do not include feedback from accreting black holes (active galactic nucleus (AGN) feedback) in our simulations as there is no evidence of AGN activity in dwarf galaxies like the one studied here. In our runs, the parameters for the SF and feedback are adjusted to match the Kroupa initial mass function as specified by Kroupa (2001). The SF timescale is set to $t_\text{SF} = 3.5$ Gyr, the cloud evaporation parameter to $A_0 = 1250$, and the SN temperature to $T_{\text{SN}} = 1.25 \times 10^8$ K.

2.1. Primary Galaxy Setup

We apply the method given by Springel et al. (2005) to construct the central galaxy. The central galaxy consists of an exponential stellar disk. In order to match the almost constant radial gas density profile of IC 2574, we have modeled the gas disk with two components: a radial exponential component and a constant radial profile which falls off rapidly at a specified scale radius. The stellar disk has a mass $M_{\text{disk}}$, the gaseous disk has a mass $M_{\text{gas}}$ with a spherical bulge with mass $M_b$ embedded in a DM halo of mass $M_{\text{DM}}$. The halo has a Hernquist (1990) profile with a scale radius corresponding to a Navarro–Frenk–White (NFW) halo (Navarro et al. 1997) with a scale length of $r_s$ and a concentration parameter $c_{\text{vir}} = R_{\text{vir}}/r_s$. We use the results of Macciò et al. (2008) to compute halo concentration as a function of virial mass. The scale lengths $r_s$ of the exponential gaseous and stellar disks are assumed to be equal, and are determined using the model of Macciò et al. (2008),
assuming that the fractional angular momentum of the total disk
\( j_d = (J_{\text{gas}} + J_{\text{disk}})/J_{\text{vir}} \) is equal to the global disk mass fraction
\( m_d = (M_{\text{gas}} + M_{\text{disk}})/M_{\text{vir}} \) for a constant halo spin \( \lambda \). This is
equivalent to assuming that the specific angular momentum of
the material that forms the disk is the same as that of the initial
DM halo, and is conserved during the process of disk forma-
tion. The vertical structure of the stellar disk is described by a
radially independent sech\(^2\) profile with a scale height \( z_0 \), and
the vertical velocity dispersion is set equal to the radial velocity dis-
perion. The vertical structure of the gaseous disk is computed
self-consistently as a function of the surface density by requir-
ing a balance of the galactic potential and the pressure given by
the EOS. The stellar bulge is constructed using the Hernquist
(1990) profile with a scale length \( r_b \).

We build a primary galaxy which matches the properties of
IC 2574 (mass profiles taken from Leroy et al. 2008). The galaxy
has a halo of mass \( M_{\text{200}} = 10^{11} M_\odot \) obtained from the stellar
mass, from the recipe given in Moster et al. (2010b), containing
a stellar disk of mass \( M_{\text{disk}} = 3.16 \times 10^8 M_\odot \), a gaseous disk
component of mass \( M_{\text{gas}} = 1.8 \times 10^9 M_\odot \) with 80\% of the gas in
the H\(_1\) disk, and a small bulge of mass \( M_{\text{bulge}} = 3.16 \times 10^7 M_\odot \).
The DM halo has a concentration parameter of \( c_{200} = 8.47 \). The
scale radius of the disk (the stellar and exponential component
of the gaseous disk) is \( r_d = 2.1 \) kpc and the scale radius of the
slab of gas is \( r_{\text{slab}} = 4.5 \) kpc. Once we fix \( r_b \) we compute the
halo spin parameter from the recipe of Mo et al. (1998)
which results in a value of \( \lambda = 0.047 \). The disk scale height
is fixed at \( z_0 = 0.15 \) kpc and the scale radius of the bulge is
set at \( r_b = 0.095 \) kpc. The galaxy has \( N_{\text{DM}} = 10^6 \) DM
particles, \( N_{\text{disk}} = 10^4 \) in the stellar disk, \( N_{\text{bulge}} = 10^4 \) in
the bulge, and \( N_{\text{gas}} = 5.7 \times 10^5 \) gaseous disk particles. The force
resolution (softening) is 101, 80, and 57 pc for dark, gas, and
stars, respectively. In order to have a stable initial condition, we
evolve this primary galaxy in isolation for 1 Gyr. The initial

conditions were chosen in such a way that the surface density of
the gas matches the observed density of IC 2574 after evolving
for 1 Gyr as shown in Figure 1.

3. SIMULATION RESULTS

Here we present the results of our numerical experiments. We
mainly run three kinds of simulations: single encounter with
a pure DM sub-halo (no gas or stars), single encounter with
a DM sub-halo containing a small gas fraction, and multiple
cosmologically motivated encounters.

These single-halo simulations are simplistic experiments
designed to explore the effect of sub-halo/disk interactions.
Orbit, mass, and gas content are not meant to represent the
typical case. A cosmologically motivated run with multiple
interactions will be presented in Section 3.3.

3.1. Pure DM Sub-halo Interaction

In this section, we investigate the dynamical impact of a pure
DM halo on the gaseous disk. The mass of the sub-halo is first
fixed at a value of \( M_{\text{sub}} = 10^8 M_\odot \). We want to have a highly
concentrated sub-halo to act like a “bullet” in the interaction. To
do this, we start with a \( M_{\text{200}} = 10^9 M_\odot \) halo and then carure out
99\% of its mass and create a \( 10^8 M_\odot \) halo. This is justified, as it
has been shown that the sub-halos passing through the primary
halo of a galaxy get tidally stripped and can lose up to 90\%—and
in some extreme cases 99\%—of their mass during their orbit (see
Peñarrubia et al. 2008; Macciò et al. 2010). The total number of
DM particles in with halo has been set to \( N_{\text{DM}} = 1000 \). Starting a lower-mass halo (e.g., \( 10^9 M_\odot \)) would have resulted
in a less concentrated “bullet,” hence our choice maximizes the
dynamical effect on the disk. This sub-halo is placed at a distance
of 5 kpc above the gaseous disk of the primary galaxy and is
assigned an initial velocity of \( v_z = 150 \) km s\(^{-1}\) perpendicular
and pointing toward the galactic disk. Figure 2 shows a surface
density map of the gaseous disk after the passage of the sub-halo.

As is shown clearly from Figure 2, a pure DM sub-halo
is unable to form a hole; instead it gives rise to a localized
high-density region (marked by a circle). This is due to the fact
that the DM particles are collisionless. Due to the lack of contact

![Figure 1](image1.png)

**Figure 1.** Red line is the gas surface density and the black line is the surface
density of stars in the inner 7 kpc of IC 2574. The observational data are
taken from Figure 27 of Leroy et al. (2008). The error bars represent the rms
uncertainty value.

(A color version of this figure is available in the online journal.)

![Figure 2](image2.png)

**Figure 2.** Surface density map of the gaseous disk after the passage of the pure
DM sub-halo of mass \( 10^8 M_\odot \). Such an encounter leads to a gas over-density
(marked by a circle). The units of density in this plot are in \( 10^9 M_\odot \) kpc\(^{-2}\).
The two-dimensional contour plots were made using the visualization software
SPLASH (Price 2007).

(A color version of this figure is available in the online journal.)
forces the sub-halo cannot push away the gas particles. DM can only gravitationally focus the gas in a stream behind its path of motion (Bondi–Hoyle accretion; Edgar 2004; Bondi & Hoyle 1944; Bondi 1952), which gives rise to higher surface density in the region it passes through. These high-density peaks are 20%–25% denser than the mean density of the disk, and they last for about 80–90 Myr; afterward they are destroyed by the dispersion of the gas and the differential rotation of the disk. The fundamental result of this first experiment is that a pure DM sub-halo is not able to create a hole in the gaseous disk.

### 3.2. Gaseous Sub-halo Interaction

Since a pure DM halo is not able to displace the gas in the disk, a medium that interacts through gravity as well as contact forces is needed in order to push the gas away from its motion path. A gaseous medium will provide the required contact forces to push the gas away and form holes. We construct the DM sub-halo with the same mass and concentration parameter as described in the previous section and in addition we also add a hot gaseous component. The hot gas has a beta profile with \( \beta = 2/3, \) a spin factor of \( \alpha = 4, \) and a core radius of 90 pc. For a more detailed description of the hot gas profile and parameters, we refer to Moster et al. (2011). These sub-halos are expected to have a very low amount of gas (if any) due to re-ionization (e.g., Okamoto et al. 2008).

Moreover we are interested in “dark” satellites, so we do not want the gas in the sub-halos to form stars; hence we choose a very low gas fraction (i.e., fraction of mass in gas relative to the DM mass) in these sub-halos: \( M_{\text{gas}}/M_{\text{DM}} \approx 0.03. \) We consider only a hot gas component as halos containing cold gas (and possibly stars) will be directly detectable while, in this work, we are interested in testing the effects of the more numerous, undetected, dark satellite population, which is predicted by the CDM model. We then place this new sub-halo on the exact same orbit of the pure DM experiment and let it interact with the gaseous disk as described in the previous section.

The hot gas in the halo is able to displace the gas in the disk and produce a low-density region (a hole), associated with an expanding high-density shock wave as shown in Figure 3. For our chosen parameters, the hole has a diameter of about 1.5 kpc and lasts for about 60 Myr. The lifetimes of the holes are decided by two factors: the pressure gradient and the differential rotation. Our simulations suggest that the pressure gradient causes the hole to be filled by gas long before it gets destroyed by the differential rotation, although differential rotation becomes important for very large holes. For typical hole sizes of 1–2 kpc we find an average hole lifetime of about 50–60 Myr, in agreement with the dynamical ages estimated by Walter & Brinks (1999).

Another interesting feature of this simulation is the enhanced SF on the rim of the hole as shown in Figure 4. New stars have preferentially formed on the high-density edges of the hole, while the hole itself contains very few new stars. This result is in agreement with the ages of the stars associated with the H\( ^{\text{I}} \) holes in IC 2574 as derived by Pasquali et al. (2008), via comparison of observed \( UBV \) colors with those predicted by synthetic stellar populations (for more details see Pasquali et al. 2008).

We then run a series of simulations for different percentages of gas fraction of the DM sub-halos, keeping all other simulation parameters constant. The effect of a pure DM sub-halo and a sub-halo containing gas are inherently different. Figure 5 shows the relative surface density profiles of the gas along a strip of width 1 kpc joining the center of the galaxy and the center of the hole, for different sub-halo gas fractions (including the case of no gas). A pure DM sub-halo (in black) produces a peak of increased density, while a gaseous halo produces a low-density region surrounded by a high density wave. This density wave increases the density in the rim of the hole above the SF density threshold (\( \rho_{\text{th}} \)), thus triggering SF all along the rim of the hole. As expected, the size of the hole and the extent to which the disk is perturbed depend upon the gas fraction of the infalling DM sub-halo.

Impact with a sub-halo will create a net velocity gradient along the sub-halo trajectory in the vertical component of the H\( ^{\text{I}} \) gas. This signature could in principle disentangle different formation scenarios for the H\( ^{\text{I}} \) holes. Figure 6 shows the velocity in the \( z \) component (perpendicular to the disk plane, \( V_{\text{z, disk}} \), which equals zero in the unperturbed case) along the same strip.

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**Figure 3.** Effect of the interaction between a DM sub-halo containing 3.2% of gas by mass (DM mass = 10^9 M_⊙). (A color version of this figure is available in the online journal.)

**Figure 4.** Star formation rate (SFR) showing clearly the ring of new stars formed along the rim of the hole. The units of SFR surface density in this plot are in 10^10 M_⊙ kpc^-2. (A color version of this figure is available in the online journal.)
as mentioned above. Here the infalling halos have two different gas fractions, 3.2% (green line) and 0.8% (red line), with a velocity of $v_z = 150$ km s$^{-1}$ and a halo with a gas fraction of 0.8% with a velocity of $v_z = 300$ km s$^{-1}$. A higher sub-halo initial velocity and/or a larger gas fraction imparts more energy to the disk in the impact direction and hence produces a stronger signature in $v_{c,\text{disk}}$. This plot shows that the effect is small and would be very hard to detect in real observations as the effect is of the same order as the typical velocity resolution of H$\text{I}$ observations of nearby galaxies (e.g., Walter et al. 2008).

### 3.3. Cosmological Runs

Our previous simplified setups have shown that DM sub-halos that contain a small fraction of gas can in principle create holes in the H$\text{I}$ distribution that resemble the observed ones. The next question to answer now is whether there are enough DM satellites to reproduce the number of observed holes in a galaxy similar to IC 2574.

To answer this question we turn to cosmological N-body simulations which give us the mass, size, velocity, and orbital parameters of sub-halos of the reference galaxy IC 2574. We use the publicly available database of satellite distribution in the Via Lactea II (VLII) simulation (Diemand et al. 2007). Unfortunately, the mass of the parent halo in the VLII simulation ($2 \times 10^{12} M_\odot$) is higher than the estimated mass of the halo of our reference galaxy IC 2574 ($10^{11} M_\odot$). We thus decide to scale down the properties of the sub-halos using the following simple dynamically motivated scaling relations:

$$M' = M/10,$$

$$v'_{x,y,z} = \frac{v_{x,y,z}}{10^{1/3}},$$

where $M'$ and $v'_{x,y,z}$ are the scaled mass and velocities, respectively. This simple scaling is valid as a first-order approximation. We use both satellite distributions (from M11 and M12) in our cosmologically motivated tests.

In order to test that we have not introduced any biases into the satellite properties by rescaling them, we run an additional N-body simulation of an $M = 10^{11} M_\odot$ DM halo, at a resolution lower than the VLII. We have selected the candidate halo from an existing low-resolution DM simulation (350$^3$ particles within 90 Mpc; see Neistein et al. 2010) and re-simulated them at higher resolution using the volume renormalization technique (Katz & White 1993). The total number of particles within the virial radius at $z = 0$ is $\approx 3.3 \times 10^6$, which gives a mass per particle of $3.05 \times 10^4 M_\odot$. We will refer to this simulation as M11, while we will use M12 for the rescaled version of the VLII simulation. Figure 7 shows that sub-halos of both runs occupy the same phase-space region, which confirms that our simple scaling is valid as a first-order approximation. We use both satellite distributions (from M11 and M12) in our cosmologically motivated tests.

These N-body simulations predict that a large number of sub-halos are present around a typical galaxy of $10^{11} M_\odot$. In fact we have 798 sub-halos from the M12 simulation and 468 from the M11 simulation, with masses larger than $10^6 M_\odot$, our resolution limit in the N-body simulations. Not all of these halos pass through the disk. Most of them have nearly circular orbits. Only a few of them have orbits which take them close enough to the center of the halo, and hence interact with the disk; these are the halos we are interested in. We find interacting halos by integrating orbits of all sub-halos in a static potential for 1 Gyr.

The shelf of high-velocity sub-halos at a given distance is due to the higher halo statistics in M12 which allow a better sampling of the tails (positive and negative) of the velocity distribution.
work (not affect the sub-halo mass function on the small scales as considered in this of 1 Gyr would in principle require $z_i \approx 100$). Each of these halos contains a gaseous halo in hydrostatic equilibrium with the DM potential. Finally, we replace our synthetic halos around the primary galaxy at the same position and with the same velocity as obtained from the $N$-body simulations.

A combination of high mass and high velocity is needed to produce holes as shown in the previous section. Due to the different orbital parameters, such as angle of impact, velocity, and mass of the halo, the lifetimes of the holes are more varied, ranging from a mere 10 Myr to as much as 70 Myr. Figure 8 shows the surface density map of the gaseous disk after 0.53 Gyr; a circular hole of about 1 kpc can be seen in the lower left corner of the simulation. The structure seen at the center of the galaxy is the result of local instabilities and SF.

We now quantify how many holes are produced with respect to observations. We focus on large holes ($R > 1$ kpc) since smaller features can be more easily explained by SN explosions, stellar winds, or a combination of both.

In both our simulation setups (M11 and M12) we observe only 3–4 events in the 1 Gyr running time (Figure 9), with no more than one hole in a particular snapshot (Figure 8). On the other hand, Walter & Brinks (1999) observed a total of eight holes with radii greater than 1 kpc in a single “snapshot” of IC 2574 (dotted line in Figure 9). The number of holes formed in the M11 run is lower primarily due to the lack of resolution (when compared to M12). This results in an underestimation of the total number of low-mass satellites.

It emerges clearly that while DM sub-halos are in principle able to create holes in the H\textsubscript{i} gas, when a cosmologically motivated sub-halo distribution is used the number of predicted halos do not match the observed one. This leads us to conclude that the sub-halo–disk interaction is not the principal mechanism creating the observed H\textsubscript{i} holes.

We note that the number of holes shown in Figure 9 is just an upper limit. So far we have assumed that DM sub-halos will keep their gas (needed to displace the gas in the H\textsubscript{i} disk) all the way down to the galaxy center, completely neglecting the effect of ram pressure. The ram pressure against the hot halo with a density contrast of $\Delta = 1000$ with respect to the critical density of the universe, as is typical for sub-halos (the density contrast for isolated virialized halos is normally assumed to be $\Delta_{vir} \approx 100$). Each of these halos contains a gaseous halo in hydrostatic equilibrium with the DM potential. Finally, we replace our synthetic halos around the primary galaxy at the same position and with the same velocity as obtained from the $N$-body simulations.

| Mass ($M_\odot$) | Number of Halos and Their Properties |
|-----------------|--------------------------------------|
|                 | $N_{H}$$\&$$M_{12}$ | $N_{H}$$\&$$M_{11}$ | $c_{200}$ | $N_{DM}$ | $N_{Gas}$ |
| $5.56 \times 10^6$ | 26 | 10 | 44.16 | 556 | 446 |
| $1.01 \times 10^7$ | 7 | 0 | 41.65 | 1010 | 799 |
| $1.46 \times 10^7$ | 3 | 2 | 40.16 | 1463 | 1158 |
| $1.91 \times 10^7$ | 0 | 0 | ... | ... | ... |
| $2.37 \times 10^7$ | 1 | 1 | 38.34 | 2371 | 1876 |

Notes. The first column denotes $M_\odot$ in units of solar mass, the second the number of halos in the M11 run, the third the number of halos in the M11 run, the fourth the concentration parameter, the fifth the number of DM particles used to sample the halo, and the sixth the number of gas particles used to sample the halo.

extracted from the N-body simulation at $z = 0.6$. An interaction is defined as the passage of the sub-halo within a cylinder of radius $R = \sqrt{x^2 + y^2} < 8$ kpc and a height $-2 < h_i < 2$ centered at the center of the halo. We obtain a sample of 37 DM sub-halos for M12 and 13 for M11, where the lower number of satellites in the M11 run is due to its lower resolution compared to the VLII simulation.

In both the M12 and M11 runs, DM sub-halo masses range between $1.1 \times 10^6 M_\odot$ and $1.3 \times 10^7 M_\odot$. We divide these halos into five halo mass bins. The number of halos in each mass bin and their properties are given in Table 1. All halos in this run have a gas fraction of 5% by mass. We assign this relatively large amount of gas in these halos so as to get an upper limit for the number of holes that can be formed.

For each of the mass bins we generate a synthetic halo using a recipe which is slightly different from the single-halo simulation presented in the previous section. We create a spherical NFW
gas surrounding the galaxy could partially or totally remove the baryonic content of the sub-halo and make it even more inefficient in producing holes. In order to test this scenario we run an additional simulation in which we turn on isotropic galactic winds while running the central galaxy in isolation for 1 Gyr to stabilize it (see Section 2). These winds preferentially expel gas perpendicular to the plane of the disk as it faces the least hindrance in this direction. This creates shells of gas surrounding the galactic plane. This gas (slightly colder than the gas inside the sub-halos) is efficient in stripping all the gas from the sub-halos.

When this new initial condition (central galaxy run with winds on) is evolved together with sub-halos of 1 Gyr, it produces virtually no holes. This experiment shows that it is indeed very difficult for the sub-halos to retain a sufficient amount of gas to perturb the central H\textsc{i} disk. This points to a different process being responsible for the production of large holes in the H\textsc{i} distribution.

4. CONCLUSIONS AND DISCUSSION

Atomic hydrogen (H\textsc{i}) observations of nearby galaxies reveal complex gas distributions. In many systems, the neutral ISM contains holes, shells, and/or cavities. In order to understand the origin of these features, we numerically investigate how the impact of DM sub-halos orbiting a gas-rich disk galaxy embedded in a massive DM halo influences the dynamical evolution of the H\textsc{i} gas disk of the galaxy. We mainly focus our attention on the creation of large holes ($R > 1$ kpc) in the H\textsc{i} distribution, commonly found in observations of nearby galaxies.

We create a central galaxy resembling the properties of the well-studied dwarf galaxy IC 2475 and bombard it with gaseous gas inside the sub-halos) is efficient in stripping all the gas from the sub-halos. Even a gas fraction as low as 0.8% in a halo of mass $10^{10} M_\odot$ with a velocity of 150 km s$^{-1}$ is able to produce a detectable low-density region. On average, holes have a lifetime of about 20–60 Myr, depending on the halo density, gas mass, and impact velocity.

We then use satellite properties directly extracted from a high-resolution $N$-body cosmological simulation (Via Lactea II) to check how many holes are predicted in the commonly assumed CDM model.

These cosmologically motivated runs show that sub-halos with a relatively high gas fraction (5%) are able to produce a total of about 3–4 large holes ($R > 1$ kpc) in an integration time of 1 Gyr. This number is significantly lower than the number of observed holes of the same size in IC 2475 galaxy. If the effect of ram pressure is taken into account, the DM satellites tend to lose a significant fraction of their gas content, making them even less efficient at perturbing the H\textsc{i} disk.

We conclude that, although DM matter satellites with a modest gas content are in principle able to create holes with a radius of order 1 kpc, the disk–sub-halo interaction is not the primary channel through which these holes form in real galaxies. We consider it likely that other astrophysical processes, such as SN explosions, stellar winds, high-velocity clouds, or a combination of the above factors, are the main causes for the observed complex geometry of extended H\textsc{i} disks.

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