SIMULATED VOID GALAXIES IN THE STANDARD COLD DARK MATTER MODEL

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Abstract

We analyze a (120 h−1 Mpc)3 adaptive mesh refinement hydrodynamic simulation that contains a higher resolution 31 × 31 × 35 h−1 Mpc subvolume centered on a ~30 Mpc diameter void. Our detailed ~1 kpc resolution allows us to identify 1300 galaxies within this void to a limiting halo mass of ~1010 M⊙. Nearly 1000 galaxies are found to be in underdense regions, with 300 galaxies residing in regions less than half the mean density of the simulation volume. We construct mock observations of the stellar and gas properties of these systems and reproduce the range of colors and luminosities observed in the Sloan Digital Sky Survey for nearby (z < 0.03) galaxies. We find no trends with density for the most luminous (Mr < −18) galaxies, however our dwarf void galaxies (Mr > −16), though they are less reliably resolved, typically appear bluer, with higher rates of star formation and specific star formation and lower mean stellar ages than galaxies in average density environments. We find a significant population of low-luminosity (Mr ∼ −14) dwarf galaxies that is preferentially located in low-density regions and specifically in the void center. This population may help to reduce, but not remove, the discrepancy between the predicted and observed number of void galaxies.

Key words: cosmology: theory – galaxies: evolution – hydrodynamics – large-scale structure of universe – methods: numerical

Online-only material: color figures

1. Introduction

A cold dark matter (ΛCDM) has proven fairly robust when compared with a wide range of existing observations (Lacey & Cole 1993; Cen et al. 1994; Zhang et al. 1995; Springel et al. 2010). Simulations can reproduce the galaxy clustering properties we observe in large redshift surveys, as well as the size of galaxy clusters. In addition, ΛCDM predicts hierarchical growth as the dominant mechanism in galaxy evolution (Peebles 1969; White & Frenk 1991).

However, discrepancies with observation remain, particularly on individual galaxy scales. Theory predicts a centrally peaked mass distribution (cusp) should dominate the shape of the dark matter density profile (Navarro et al. 1996, but see Governato et al. 2010), while observations show that a wide range of halo sizes, from galaxy clusters to dwarf spheroidals, may instead have cored profiles (Tyson et al. 1998; Klyna et al. 2003; Walker et al. 2009). Simulations have difficulty reproducing exponential, bulgeless disks, and observations within the Local Volume disagree with predictions of where we should find the largest disk galaxies (Peebles & Nusser 2010; Kormendy et al. 2010). The missing satellite problem describes from the overprediction of small dark matter halos clustering around the Milky Way (Klypin et al. 1999; Moore et al. 1999; Simon & Geha 2007). CDM simulations result in the overprediction of the number of low-mass halos existing within voids (Peebles 2001). One key to solving these problems may come from the inclusion of sufficient physics to properly simulate the baryon content of galaxies, which does not dominate their mass but contributes significantly to small-scale dynamics and observables, such as stars or gas.

Early cosmological simulations of voids were based on dark matter only, N-body simulations (e.g., Ryden & Turner 1984; White et al. 1987; Little & Weinberg 1994; Vogele et al. 1994; Mathis & White 2002). These authors compared the dark matter distribution with the void statistics in large surveys such as the Center for Astrophysics Redshift Survey and the Las Campanas redshift survey, in terms of their sizes and abundances. Using semi-analytic prescriptions for galaxy formation on outputs from N-body simulations, Patiri et al. (2006) studied the colors and specific star formation rates (SFRs) of void galaxies, finding that there are more blue galaxies in void but no systematic differences between void galaxies and the general galaxy population. Ceccarelli et al. (2006) used a similar method to study void dynamics and the effect of redshift distortions in void identification. The only cosmological hydrodynamic simulations run to date focusing on voids are Viel et al. (2008), who analyzed the void statistics at z ∼ 2, and Hoeft et al. (2006), who investigated the effect of the cosmological UV background on the formation of dwarf galaxies in voids.

We have selected a void region from within a full (120 h−1 Mpc)3 cosmological simulation, and we examine with moderate resolution the dark matter, gas, and stars of a large sample of galaxies located within and around this large void. We employ an adaptive mesh refinement (AMR) code to reproduce the gas physics on a scale of 1 kpc. Observationally, void galaxies are distinguishable from galaxies in average or overdense environments as they are typically less luminous, and at fixed luminosity are bluer, with higher rates of star formation and specific star formation (Rojas et al. 2004, 2005). This is not strongly reflected in their gas content, though they are generally gas-rich, as their total mass in H1 is fairly typical for their luminosities (Szomoru et al. 1996; Kreckel et al. 2011b).

We compare the integrated properties of void galaxies from our simulation, described in Section 2, both with observed void galaxies and galaxies in higher density regions within this simulation. We present our results in Section 4 and our conclusions are summarized in Section 5.
2. SIMULATION INITIAL CONDITIONS AND PHYSICAL PROCESSES

We perform cosmological simulations using the AMR Eularian hydro code, Enzo (Bryan 1999; Norman & Bryan 1999; O’Shea et al. 2004), with a periodic box of size 120 $h^{-1}$ Mpc comoving on a side and cosmological parameters taken from the WMAP5 ΛCDM results combined with measurements of Type Ia supernovae and baryon oscillations in the galaxy distribution (Hinshaw et al. 2009) $(Ω_m, Ω_Λ, Ω_b, h, σ_8, n_s) = (0.279, 0.721, 0.0462, 0.701, 0.817, 0.960)$. We first run a low-resolution simulation with a uniform dark matter particle mass of $7.6 \times 10^{10} M_\odot$, 128$^3$ root grid cells, and only four levels of refinement from an initial redshift of $z = 99$ to 0. Based on the $z = 0$ output of this simulation, a large void region having a diameter of $\sim 30 h^{-1}$ Mpc was identified (see also Cen 2010). Tracing the dark matter particles back to the initial redshift of $z = 99$ showed that the void region expands with time in terms of comoving volume, as expected. To achieve high mass and spatial resolution, we then use the multimass initialization technique and employ three nested volumes with successive particle masses decreased by a factor of eight. Hence, the innermost $31 \times 31 \times 35 h^{-1}$ Mpc$^3$ comoving volume, sufficiently large to contain the identified void volume at $z = 0$, has a dark matter particle mass of $1.5 \times 10^9 M_\odot$. Within this innermost nested volume, hydrodynamic refinements were allowed beginning with a root grid cell size of $937 h^{-1}$ kpc and a maximum refinement level of $l_{\text{max}} = 10$, resulting in a maximum resolution of $0.916 h^{-1}$ kpc at $z = 0$.

The simulation includes a metagalactic UV background (Haardt & Madau 1996), a diffuse form of photoelectric and photoionization heating (Abbott 1982; Joung & Mac Low 2006), and shielded UV radiation by neutral hydrogen (Cen et al. 1995) extended down to 10 K (Dalgarno & McCray 1992), which requires that the gas within that cell be contracting, cooling rapidly, and gravitationally unstable. Under these conditions, a stellar particle of mass $m_s = c_s m_{gas} \Delta t / t_s$ is created to replace gas from that cell and is tagged with its initial mass, creation time, and metallicity. Here, $\Delta t$ is the time step, $t_s = \max(t_{\text{dyn}}, 3 \times 10^6 \text{ yr})$, $t_{\text{dyn}} = \sqrt[3]{3\pi / (32 G \rho_{\text{gas}})}$ is the dynamical time of the cell, $m_{gas}$ is the baryonic mass in the cell, and $c_s = 0.03$ is the star formation efficiency. Star particles typically have an initial mass of $\sim 5 \times 10^6 M_\odot$. Star formation and supernovae feedback are modeled following Cen et al. (2005) with a supernovae efficiency of $e_{\text{SN}} = 10^{-5}$. Star particle masses decay slightly as feedback energy and ejected metals are distributed into the 27 local gas cells, weighted by the specific volume of each cell, and centered at the star particle in question. The temporal release of metal-enriched gas and thermal energy at time $t$ has the following form:

$$f(t, t_i, t_{\text{dyn}}) \equiv (1/t_{\text{dy}n})(t - t_i) / t_{\text{dy}n} \exp(- (t - t_i)/t_{\text{dy}n}),$$

where $t_i$ is the formation time of a given star particle. The metal enrichment inside galaxies and in the intergalactic medium is followed self-consistently in a spatially resolved fashion (Cen et al. 2005). Recently, Cen (2010) used a simulation of the same system with a higher spatial resolution (by a factor of two) to study the nature of damped Lyα systems.

3. MOCK OBSERVATIONS WITHIN THE SIMULATION VOLUME

We identify virialized objects in our high-resolution simulations using the HOP algorithm (Eisenstein & Hut 1998) with the threshold parameter $(\delta_{\text{outer}})$ of 125. For identifying galaxies, we used higher $\delta_{\text{outer}}$ values of $10^2$ and $10^3$ to additionally find subhalos located within virialized objects. Galaxies are excluded that are outside of the central, high-resolution $\sim (30 h^{-1} \text{ Mpc})^3$ region, or that contain any coarse dark matter particles more massive than the highest particle resolution achieved. We also exclude any dark matter halos with fewer than 100 particles within the virialized region to ensure sufficient resolution of the physical balance between pressure and self-gravity within the simulated galaxies. For this work, we have extracted the hydrodynamic data around every identified galaxy at a uniform resolution corresponding to level 8, or a physical scale of $3.66 h^{-1}$ kpc at $z = 0$, as it is sufficient for our examination of the integrated properties in these systems and significantly speeds our analysis.

The light distribution is computed from the star particles using the Galaxy Isochrone Synthesis Spectral Evolution Library (GISSEL) stellar synthesis code (Bruzual & Charlot 2003). We calculate the luminosities of the simulated galaxies in the five Sloan Digital Sky Survey (SDSS; Abazajian et al. 2009) bands (ugriz). Internal extinction corrections were applied by considering the mass column density of metals, $\Sigma_Z$, along the line of sight within the virial radius for a randomly chosen viewing direction along the simulation volume axes. Starting with the observational relation determined in the Milky Way at solar metallicity (Binney & Merrifield 1998),

$$A_V = \frac{N(H_{100})}{1.9 \times 10^{21} \text{ cm}^{-2}} \text{ mag},$$

we allow for some dependence on metallicity, and scale for the fraction of refractory elements, $f_{Fe}$ (Vladilo 2004). Thus we find that

$$A_V = \frac{\Sigma_Z f_{Fe}}{F m_p 4 \times 10^{19} \text{ cm}^{-2}} \text{ mag.}$$

We choose a scaling factor, $F = 1.5$, to match our simulated extinction with the observational relation (Equation (1)) for those simulated galaxies with solar metallicity. We also consider the observational dust-to-gas relation determined in the Large Magellanic Cloud (LMC), which has a much larger uncertainty, as compared to 1/3–1/2 solar metallicity simulated galaxies (Koornneef 1982). We find a best fit with a factor of $F \sim 3$, however a factor of $F = 1.5$ is still in agreement within the errors, which are quite large, and we adopt this value for the remainder of this paper. Extinctions for each star particle were then scaled to the central wavelength for each of the five SDSS bands following Calzetti et al. (2000). We define the integrated stellar parameters (i.e., mass, luminosity, SFR) of each simulated galaxy to be the sum of the properties of the star particles located within 15% of the virial radius of the galaxy at a given redshift.

The dark matter density field was determined by calculating the mean dark matter density for the entire simulation volume, gridding all dark matter particles to a $1 h^{-1}$ Mpc grid, then applying a $5 h^{-1}$ Mpc three-dimensional Gaussian smoothing filter. The smoothing length was chosen to agree with the
galaxy correlation length observed in large redshift surveys (Jing et al. 1998; Park et al. 2007). We also note that our choice of smoothing length assigns a reasonable dark matter density contrast of \( \delta \rho / \rho < -0.5 \) to all galaxies where the distance to the third nearest neighbor is greater than 7 \( h^{-1} \) Mpc, which was the more restrictive void galaxy selection technique used by Rojas et al. (2004).

4. RESULTS

Of a total of 1268 galaxies with high-resolution hydrodynamic simulation, none are found at positions with a dark matter density contrast (see Section 3) of more than 1 as we include only filaments and walls bounding the void but no massive clusters. Nine hundred fifty galaxies are found at locations with \( \delta \rho / \rho < -0.5 \) to 0, from which we form a void sample (VS) of 648 galaxies with \( \delta \rho / \rho < 0 \), and 302 galaxies that are in regions with \( \delta \rho / \rho < -0.5 \) form a low-density void sample (LVS). There are also 318 galaxies that make up a non-void sample (NV) at roughly average densities (0 < \( \delta \rho / \rho < 1 \) ) on the void boundaries (Table 1 and Figure 1). We make these divisions in part to facilitate direct comparison with observed void samples (Rojas et al. 2004, 2005). We can also define the distance, \( R \), from the void center at \([64, 71, 45]\) \( h^{-1} \) Mpc, as identified within the full 120 \( h^{-1} \) Mpc box, and find that only two galaxies resolved by the simulation are within 5.5 \( h^{-1} \) Mpc and no NV galaxies are within 18 \( h^{-1} \) Mpc. We use this to additionally define a void center sample (VC) of 176 galaxies within 18 \( h^{-1} \) Mpc. Simulated observations were made with a typical H\(_{\text{I}}\) column density detection limit of \( 1 \times 10^{19} \) cm\(^{-2}\), and resulting integrated H\(_{\text{I}}\) column density contours overlaid on simulated observations of the stellar luminosity (Figure 2).

We apply a Kolmogorov–Smirnov test to determine if the luminosity distribution of these samples could be drawn from the same parent population. The probability that the LVS or VC samples are drawn from the same population as the NV sample is fairly low (\( P < 0.03 \)), however there is a very strong probability (\( P = 0.847791 \)) that the VS sample is drawn from the same population as the NV sample. This suggests that there is a sharp distinction between the galaxy populations in the deepest underdensities and those in more moderately underdense regions. This is most apparent in the large population of low-luminosity galaxies found preferentially in the void center (see Section 4.5).

4.1. Luminosity Function

As the most luminous galaxies have been more robustly simulated throughout their merger history, we expect that this population will most closely match observations. Indeed, the observed void galaxy luminosity function is very well reproduced (Figure 3). Here we have divided our sample into two at \( \delta \rho / \rho < -0.4 \), following Hoyle et al. (2005), and contrast the lower density void galaxies with the higher density “wall” galaxies. Our simulated void sample very closely matches their observationally determined Schechter function fit. Our “wall” sample contains too few galaxies, however our volume excludes any significant high-density regions and a significant number
Figure 2. Simulated observations of LVS galaxies, with sample-observed void galaxy (bottom right) for reference. Gray scale indicates $g$-band emission, and contours show H\textsc{i} column densities of $5 \times 10^{19} \text{cm}^{-2}$ plus increments of $10^{20} \text{cm}^{-2}$ with a maximum of $1.25 \times 10^{21} \text{cm}^{-2}$. The observed void galaxy VGS\textunderscore 32 (bottom right), described in Kreckel et al. (2011b), shows the H\textsc{i} beam shown in the lower left. The simulated and observed galaxies have roughly the same luminosity and H\textsc{i} extent, and in general the agreement is good. However, the simulated galaxies have significantly more low column density H\textsc{i}.

Figure 3. Luminosity function of simulated void and “wall” galaxies. Following Hoyle et al. (2005), we split our sample into void galaxies with $\delta \rho/\rho < -0.4$ (triangles) and identify the remainder as “wall” galaxies (circles), with the respective observationally determined Schechter function overplotted. The simulated void galaxies well reproduce observations, and we underpredict the function in the “wall” sample as our simulation volume excludes higher density regions.

of galaxies contaminated by coarse particles. The turnover in both samples at $M_r = -18.5$ indicates the completeness limits in our simulated galaxy samples, and we expect that increased resolution would not significantly change our results for galaxies above this luminosity threshold.

4.2. Colors

Compared to observations, our simulated void galaxy colors appear consistent, however they do not differ greatly from the non-void galaxies. Table 2 compares the mean properties of our galaxy samples with the photometric study by Rojas et al. (2004), who construct a void galaxy sample of those galaxies with a third nearest neighbor distance greater than $7 \ h^{-1} \text{Mpc}$ and a wall sample of the remaining galaxies. Duplicating the magnitude limit ($-17.77 > M_r > -22.5$) for their distant galaxy sample, and subsequently dividing it into a bright ($M_r < -19.5$) and faint ($M_r > -19.5$) subsamples, we see no consistent trend with density in our galaxy colors, but a strong dependence on magnitude. In all magnitude-limited samples, we note that the NV galaxies are too blue when compared to the Rojas et al. (2004, 2005) wall sample.

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Figure 4. Color–magnitude diagram. On the left, the LVS (blue circles) is in reasonable agreement with the observed VGS sample (red squares). On the right, the NV (black circles) roughly traces the SDSS distribution for galaxies at redshifts $0.1 < z < 0.3$. We see no bimodality in the colors of either simulated galaxy sample such as is observed in void and field galaxies (von Benda-Beckmann & Müller 2008).

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

Figure 5. Color–magnitude diagram for the NV. On the right, the sample has been split into red (filled circles) and blue (open circles) galaxies following the $u - r = 2.2$ cut identified by Strateva et al. (2001). In each, the mean for the NV galaxies is overplotted in black. Also shown is the mean for galaxies in the void outskirts ($0.5 < \delta < 1.0$, in green) and the mean for galaxies in the deepest underdensities ($\delta < 0.5$, in blue). Among the dwarf galaxies, the void galaxies are somewhat bluer than the galaxies in average density environments.

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

Table 2

| Property | LVS | VS | NV | Rojas Void | Rojas Wall |
|----------|-----|----|----|------------|------------|
| $g - r$ | $0.586 \pm 0.0144$ | $0.600 \pm 0.0093$ | $0.589 \pm 0.0133$ | $0.615 \pm 0.007$ | $0.719 \pm 0.002$ |
| SFR | $0.988 \pm 0.0838$ | $1.80 \pm 0.172$ | $2.57 \pm 0.394$ | $0.734 \pm 0.025$ | $0.747 \pm 0.007$ |
| S-SFR ($\times 10^{-11}$) | $12.9 \pm 1.17$ | $15.0 \pm 1.65$ | $14.3 \pm 1.80$ | $3.744 \pm 0.007$ | $2.629 \pm 0.034$ |
| $g - r$ | $0.593 \pm 0.0234$ | $0.656 \pm 0.0145$ | $0.666 \pm 0.0169$ | $0.686 \pm 0.009$ | $0.765 \pm 0.002$ |
| SFR | $1.99 \pm 0.318$ | $4.30 \pm 0.5309$ | $6.54 \pm 1.01$ | $1.136 \pm 0.063$ | $0.920 \pm 0.016$ |
| S-SFR ($\times 10^{-11}$) | $8.31 \pm 1.02$ | $8.30 \pm 0.753$ | $12.1 \pm 4.09$ | $3.133 \pm 0.169$ | $2.137 \pm 0.004$ |
| $g - r$ | $0.585 \pm 0.0169$ | $0.579 \pm 0.0113$ | $0.550 \pm 0.0171$ | $0.567 \pm 0.009$ | $0.645 \pm 0.003$ |
| SFR | $0.770 \pm 0.0606$ | $0.838 \pm 0.0544$ | $0.618 \pm 0.0548$ | $0.508 \pm 0.0237$ | $0.530 \pm 0.009$ |
| S-SFR ($\times 10^{-11}$) | $13.9 \pm 1.39$ | $17.6 \pm 2.25$ | $15.3 \pm 1.79$ | $4.146 \pm 0.137$ | $3.349 \pm 0.005$ |

In addition, none of the samples exhibit bimodality of galaxy colors with a red sequence and blue cloud (Figure 4) such as is observed in both void and field galaxies (von Benda-Beckmann & Müller 2008). We compare the LVS with the geometrically selected Void Galaxy Survey (VGS; K. Kreckel et al. 2011, in preparation; selection criteria described in Kreckel et al. 2011b), and the NV with a magnitude-limited sample of SDSS galaxies selected at redshifts $0.1 < z < 0.3$. Both comparisons show general agreement between simulation colors and observations down to the observational limit $M_r \sim -16$. The choice of a lower scaling factor, $F$, in Equation (2) corresponds to more extinction and redder galaxies, however it affects void and non-void colors similarly, does not affect the bimodality, and produces an excess of low-luminosity red galaxies compared to the VGS. The lack of bimodality in color in the NV sample (Figure 5) suggests that the homogeneous distribution of galaxy colors is independent of density.

While the absolute value calculated for our galaxy colors may not be entirely reliable, we may still consider relative differences between the void and non-void samples. von Benda-Beckmann & Müller (2008) detect a slight blueward shift of the blue cloud galaxies that are deeper inside the void at fixed luminosity. Considering the mean color at fixed luminosity (Figure 5, left), we see no such shift at the high-end...
4.3. H\textsubscript{i} Properties

The H\textsubscript{i} distribution typically forms a disk, however the \(\sim5\) kpc resolution used for the extraction of the hydro variables is insufficient to attempt any analysis of the internal gas disk kinematics. The H\textsubscript{i} surface density profiles we find rise too steeply at the outskirts of the disks, often achieving fairly high column densities of \(\sim10^{21}\) cm\(^{-2}\) far outside the stellar disk (Figure 2, right; cf. Swaters et al. 2002). This inaccurate density profile persists even if we are careful to include in the integrated H\textsubscript{i} map only H\textsubscript{i} that is above a detectable level \((1 \times 10^{19}\) cm\(^{-2}\)) for modern instruments. We believe our measured H\textsubscript{i} masses to be an upper limit based on two limitations with this simulation. First, the conversion of H\textsubscript{i} to H\textsubscript{2} through formation of H\textsubscript{2} on dust grains was not properly modeled even at this resolution. This should result in an overestimate of the H\textsubscript{i} mass in the highest density, central regions of the gas disk. Second, interstellar UV ionizing radiation by individual galaxies was neglected, which would have reduced H\textsubscript{i} in the outskirts of the disk, because it is likely that local ionizing radiation is larger than the meta-galactic background.

The resulting overestimate of the H\textsubscript{i} mass is apparent in comparing the H\textsubscript{i} mass-to-light ratio to observations (Figure 6, left). It shows the same decreasing trend with increasing luminosity, however the overall value is about a factor of three too high compared with typical galaxies (Verheijen & Sancisi 2001; Swaters et al. 2002) or with void galaxies (Kreckel et al. 2011b). We note that there is a slight trend with density among our three density-selected samples (Figure 6, right), however when we examine the specifics of the trend, particularly for low-luminosity and dwarf galaxies (Figure 7), it is not very pronounced and certainly much weaker than the trend observed for dwarf galaxies by Huchtmeier et al. (1997). We see no trend as a function of distance from the void center for our VC galaxies.

4.4. Star Formation and Stellar Properties

Although there is no strong change in the SFR at lower densities (Table 2), it is clear from Figure 8 that there is a strong dependence of SFR on luminosity. Thus, we also consider the SFR scaled to the stellar mass (specific SFR, S-SFR), which is significantly increased for observed void galaxies, but unchanged within the error in the mean for our simulation (Table 2). We do, however, see significantly higher SFR and S-SFR for those lowest luminosity dwarf galaxies with \(M_r > -16\) in underdense regions when compared to our NV galaxies (Figures 8 and 9, left). The simulation does not reproduce the observed trend for increased SFR per H\textsubscript{i} mass at lower densities (Kreckel et al. 2011b), and there is good agreement...
between densities for all but the faintest dwarf galaxies (Figure 9), however our H i masses are only upper limits and our sample is not complete for low-mass galaxies.

We find no trend in the mass–metallicity relation with density (Figure 10), or with distance from the void center. This is likely because metal enrichment is mostly due to self-enrichment, and thus depends more on halo mass than large-scale environment. We reproduce the observed increase in metallicity with increasing stellar mass, but find no trend with density. The observed relation, normalized to Z⊙ at 12 + log(O/H) = 8.69 (Allende Prieto et al. 2001) with 1σ error bars indicated by the shaded region, is somewhat higher as the measurements were done in the galaxy centers where metallicity is typically enhanced. We reproduce the mass–metallicity relation for the Milky Way, with Z⊙ at M∗ = 5 × 10^10 M⊙, and the LMC, with Z⊙/2 at M∗ = 5 × 10^9 M⊙.

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

Figure 9. S-SFR (left) and SFR/H i mass (right). The LVS (blue) and VS (green) are somewhat higher than the NV (black) for the faintest galaxies, but consistent with each other and with the void galaxies observed by Kreckel et al. (2011b, red circles). The rather large discrepancy between observed and simulated values in the SFR per H i mass are consistent with the large discrepancy in the H i masses (see Figure 6).

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Figure 10. Mass-weighted metallicity as a function of stellar mass for the LVS (blue) with the mean overplotted for LVS, NV (black), and VS (green). We reproduce the same trend as Tremonti et al. (2004, red) for increasing metallicity with increasing stellar mass, but find no trend with density. The observed relation, normalized to Z⊙ at 12 + log(O/H) = 8.69 (Allende Prieto et al. 2001) with 1σ error bars indicated by the shaded region, is somewhat higher as the measurements were done in the galaxy centers where metallicity is typically enhanced. We reproduce the mass–metallicity relation for the Milky Way, with Z⊙ at M∗ = 5 × 10^10 M⊙, and the LMC, with Z⊙/2 at M∗ = 5 × 10^9 M⊙.

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Figure 11. Fraction of galaxies with a given luminosity for the VC (blue dashed line), LVS (blue), NV (black), and VS (green). The excess of low-luminosity galaxies is most apparent in the VC sample and relatively less dominant as a function of density, suggesting that this population is a result of the large-scale underdensity.

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

4.5. Excess of Low-luminosity Galaxies

One surprising discovery is the population of low-luminosity galaxies apparent below the observational survey limit in the color–magnitude diagram (Figure 4). While these galaxies do inhabit the lowest mass dark matter halos, we believe that this excess is not a resolution effect as it persists into halos ~3 times more massive than we can reliably resolve and has a strong trend with density. Figure 11 shows we have a slight excess of M∗ ~ −14 for galaxies apparent below the observational survey limit in the color–magnitude diagram (Figure 4). While these galaxies do inhabit the lowest mass dark matter halos, we believe that this excess is not a resolution effect as it persists into halos ~3 times more massive than we can reliably resolve and has a strong trend with density. Figure 11 shows we have a slight excess of M∗ ~ −14 for our NV, a noticeable excess for the VS, and a substantial excess for the LVS. In the VC this excess is particularly notable. This excess may be due in part to the youth of galaxies in the underdense regions (Figure 12), although at M∗ = −14 the mean ages are about the same. We note that while these galaxies are sufficiently resolved at z = 0, the galaxies that formed them earlier in their merger history presumably were not, so their integrated properties are correspondingly less reliable than in more massive galaxies. For example, these galaxies are generally gas-rich, with masses ~10^9 M⊙, which may be due to decreased gas consumption at earlier times resulting from simulation resolution limits.

While complete volume-limited samples of dwarf galaxies are not yet possible, comparison with observations show that our simulated dwarf galaxies are distinctly too red (Figure 13). Here we compare with dwarf galaxies within the Local Volume that have integrated B- and V-band observations (Makarova 1999;
Makarova et al. 2002, 2009), and with dwarf galaxies identified within the SDSS redshift survey (Geha et al. 2006). We convert ugri colors for the SDSS and simulated galaxy samples to Johnson–Cousins UBVRI colors following the prescription of Jester et al. (2005). In Figure 4 (right), when comparing our NV galaxy colors with typical SDSS galaxies, the simulated low-luminosity galaxy population appears almost as an extension of the red sequence while the observed dwarf galaxies (Figure 13) appear more continuous with the blue cloud. While the observational samples are not complete in any way, there is no bias for color in their selection, and both samples should be sensitive to a redder dwarf galaxy population such as we simulate. This suggests that our simulated colors for the lowest mass galaxies, which contain very few star particles, are not realistic, presumably due to resolution effects earlier in their merger histories.

Despite the discrepancy in colors, the increased number of simulated dwarf galaxies in the lowest density regions may present a way to reduce the discrepancy between the number of dark matter halos predicted within voids and the number of galaxies observed (Peebles 2001). Tinker & Conroy (2009) suggested a sufficiently tailored halo occupation distribution could solve this problem and predict that the maximum halo mass (and thus luminosity) will increase as a function of distance from the void center. We see no such relation for VC galaxy luminosities, though we do see a slight trend with dark matter halo mass but not nearly as steep a cutoff (Figure 14).

Comparing the number density of void galaxies in our simulation, which is likely a lower limit due to imperfect resolution, with the most sensitive observational surveys we still overpredict the number of void galaxies. If we consider observations of the Local Volume, where the galaxy sample within 8 Mpc of us is thought to be fairly complete to $M_B = -12$ (Tikhonov & Klypin 2009), and consider its overlap with the Local Void, which has a center 23 Mpc away from us and extends roughly 20 Mpc in radius (Tully et al. 2008), we find one void galaxy per 394 Mpc$^3$. In our simulation the luminosity limit is lower, but from our VC sample we expect a similar volume should yield about six galaxies. This is somewhat smaller than the factor of 10 discrepancy found by Tikhonov & Klypin (2009), but still quite pronounced. It is still possible that these dwarf galaxies in the voids are of low surface brightness and thus have been largely missed by existing surveys. Future simulations with increased stellar resolution may be able to constrain the surface brightness of these systems.

The one galaxy located in both the Local Volume and the Local Void, KK 246, has $M_B = -13.7$, a color$^4$ of $B - R = 1$, and a significant H i mass (Kreckel et al. 2011a). Again it is too blue, but otherwise it is in good agreement with the expected properties of our low-luminosity void galaxy population. All sky HI surveys are on the verge of reaching the sensitivity needed to detect these galaxies, HIPASS can detect galaxies with $10^8 M_\odot$ to distances of $\sim 10$ Mpc, just within the edge of the Local Void. ALFALFA reported no detections within the Pisces–Perseus foreground void with a detection limit of $10^9 M_\odot$ (Saintonge et al. 2008), however considering the discrepancy between the H i masses of our simulated galaxies compared to observations, detailed examination of closer voids within 20 Mpc where we are sensitive to $\sim 10^7 M_\odot$ may be necessary.

5. CONCLUSION

We have run cosmological simulations using the AMR Eulerian hydro code, Enzo, with a moderate resolution refined region $31 \times 31 \times 35 h^{-1}$ Mpc centered on a large $\sim 30 h^{-1}$ Mpc diameter void. We have constructed mock observations of the integrated properties (color, SFR, gas content, etc.) in a sample of roughly 900 void galaxies, 300 in especially low-density regions and 200 located well within the void center, and 300 additional galaxies in the surrounding average density filaments. The same realization of this simulation output at a higher resolution, as well as an additional simulation focused on a galaxy cluster, has found that the damped Ly$\alpha$ statistics are consistent with observations (Cen 2010).

These and other simulations run within the same framework with similar physical prescriptions have been broadly consistent with observations (e.g., Nagamine et al. 2006; Kim et al. 2009). Given the general difficulty in hydrodynamic simulations of reproducing observations (Mayer et al. 2008), we are able to accurately reproduce the range of galaxy luminosities and colors observed, but are unable to reproduce the observed bimodality in galaxy colors. At low luminosities ($M_r > -16$), where we are more affected by resolution effect from earlier in the galaxy merger history and beyond the scope of most observational studies, we see that void galaxies are bluer with higher SFR.

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$^4$ The mean color for our simulated low-luminosity galaxies with $M_B > -16$ is $B - R \sim 1.3$. 

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Figure 12. Mean stellar ages as a function of luminosity for the LVS (blue) with the mean overplotted for LVS (blue solid), VC (blue dashed), NV (black), and VS (green). The low-luminosity void galaxies are somewhat younger than the non-void galaxies.

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

Figure 13. Comparison of simulated NV low-luminosity galaxy colors with observational samples of dwarf galaxies from the Local Volume (red squares; Makarova 1999; Makarova et al. 2002, 2009) and from the SDSS (blue triangles; Geha et al. 2006). Error bars reflect uncertainties in the color conversion from SDSS ugri bands to Johnson–Cousins UBVRI bands. Simulated dwarf galaxies are distinctly redder than observed dwarf galaxies.

(A color version of this figure is available in the online journal.)
and S-SFR, but we see no trend for the brightest galaxies ($M_r < -18$).

The gas content of all our simulated galaxies is anomalously high, roughly three times what is expected for their luminosity when compared with observations, and their radial extent too large, both of which we interpret as a result of limitations in the implementation of chemistry and radiative transfer in the simulations. Taking that into account, we do reproduce the trend for fainter galaxies to have relatively more H\textsc{i} for their luminosity, but find no trend with density or distance from the void center. We reproduce the general mass--metallicity trend observed in SDSS galaxies, and we see no trend with density.

We do not see the strong segregation of the most luminous galaxies to the void edges predicted by Tinker & Conroy (2009), however we do see that the most massive dark matter halos avoid the void center. We observe a significant population of low-luminosity ($M_r \sim -14$) dwarf galaxies that is preferentially located in low-density regions and specifically in the void center. This population is too faint to be detected in most large-scale redshift surveys, however studies of the Local Void may soon become sensitive to this population, where we do observe a relatively lower median luminosity (Nasonova & Karachentsev 2011).

While omission of some physical effects, such as local sources of UV radiation from galaxies and active galactic nucleus (AGN) feedback, may ultimately affect the details of our resulting simulated observations, we emphasize the remarkable general agreement we find with observations without any tuning of the input parameters. As a matter of fact, the only adjustable parameter, aside from the unavoidable finite numerical resolution, is the feedback strength from supernovae that is essentially fixed by the theory of stellar interior and independent observations of supernovae. The supernova feedback parameter is essentially left unadjustable given the broad agreement between our simulations and observations of damped Ly\alpha systems (Cen 2010) that depends sensitively on this parameter. Future work should examine whether or not some of the discrepancies with observations may be explained by inclusion of additional baryonic physics. Of the possible astrophysical processes, given the observational lack of connection between gas-rich spiral galaxies and AGN activities, it would seem likely that AGN feedback is probably unimportant with respect to neutral gas in the vicinities of spiral galaxies. A detailed treatment of radiative transfer that includes both UV background and local UV sources will be examined in our future work. At this time, on the scales that we have examined, we are not compelled to suggest that any alteration of the current standard CDM paradigm is required.

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Figure 14. $M_r$ (left) and $M_{\text{DM}}$ as a function of distance from the void center. We see no trailing of low-luminosity galaxies into the void, however the dark matter halos do seem to segregate by mass.
