The Void Problem and an HI (wishful) Perspective on Minihalos

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The Void Problem

Scenario set by Peebles 2001:
- $\Lambda$CDM simulations show voids not being empty: they contain lower mass halos that “seem to be capable of developing into observable void objects”
- Observations, however, seem to indicate that the spatial distribution of dwarf galaxies is remarkably similar to that of brighter galaxies
  ➔ faint galaxies do not show a strong tendency to fill the voids, so...

with Snow White we ask

Where are the Dwarfs?

Disclaimer: this is NOT part of Jim Peebles’ paper
The Void Problem rationale:

• Since voids have densities ~1/10 of the mean and they occupy a large volume fraction, lots of void objects should be observed.

• At high z, the density of regions that eventually will develop into voids is not very different from the average. Hence, fluctuations should grow and halos form. The number of collapsed halos per comoving volume should be ~preserved.

• The key assumption, in saying that there is a “Void Problem”, is that $\Lambda$CDM predicts the existence of many more dwarf galaxies than observed. Does it?

A little about observations…
**Hoyle et al. (2005)** used a NN3 to extract a sample of 1010 “void” galaxies, defined as objects residing in regions with on scale of 10 Mpc, and a sample of 12732 “wall” galaxies, from SDSS DR1-2.

**Void LF:**

\[
\Phi^* = (0.19 \pm 0.04) \times 10^{-2} h^3 Mpc^{-3}
\]

\[
M_r^* - 5 \log h = -19.74 \pm 0.11
\]

\[
\alpha = -1.18 \pm 0.13
\]

**Wall LF:**

\[
\Phi^* = (1.42 \pm 0.3) \times 10^{-2} h^3 Mpc^{-3}
\]

\[
M_r^* - 5 \log h = -20.62 \pm 0.08
\]

\[
\alpha = -1.19 \pm 0.07
\]

**Void galaxies are typically fainter (M*) than Wall galaxies, but there is no significant excess of dwarfs (\(\alpha\)) to populate the voids.**

Within fixed luminosity bins, Void galaxies are also bluer, have smaller total stellar mass and higher SFR than Wall galaxies (Rojas et al. 2004, 2005)
Basilakos et al (2007)

Using the results of HIPASS, they detect a marginal signal suggesting that low HI mass sources are more likely to inhabit low density regions than high HI mass sources.

They propose that low mass HI galaxies “could be the typical population of galaxies in void-like regions”.
Within the pop. of gas-rich systems, lower HI mass systems tend to favor inhabiting the lower density regions.
No overabundance of faint, HI-rich galaxies to fill the voids

The Zwaan et al. 2003 HIMF, based on HIPASS, includes 12 galaxies with \( \log M_{\text{HI}} < 7.5 \)

With <1/4 of ALFALFA processed, we have 122
$N_{\text{Catalog}} = 2173$

$\phi' = 0.00283$

$log(M_*) = 9.795$

$\alpha = -1.33$
The faint end slope of the HI Mass Function is the same as that of the “Blue Cloud” galaxies of SDSS.
Grey contours: optical volume limited at $M_B = -19.0$
Color contours: HI volume limited at $\log(M_{HI}) = 9.2$ solar

Grey dots: optical galaxies with $M_B > -18$.
Orange dots: HI galaxies with $\log(M_{HI}) < 8$. Msun

- In a simulated volume of 120 Mpc, 20 voids with R>13 Mpc were identified, filling ~20% of the total volume. Such voids contain no halos with mass > 2.5x10^{11} Msun.
- The structure of the DM distribution in voids is similar to that seen in other density regimes: filaments, empty regions and concentrations where filaments cross. However, more massive “nodes” appear to prefer the outer parts of the voids and their masses are scaled down by a few orders of magnitude – so that the “nodes” correspond to the halo mass of a L\textless L^* galaxy, rather than a cluster.
- The edges of voids outlined by the most massive halos (M\approx 10^{12} Msun) are almost the same as those outlined by lower mass halos. The “typical” void dweller is a halo of 1-2x10^9 Msun.

• The void halo mass function is steeper on the high end than that of galaxies in other density regimes; more massive halos are deficient in voids.

• The five largest voids in the simulation have avg. radius of ~14 Mpc. Inside one of such voids, about ➔ ~50 halos with $V_c > 50$ km/s (M>1.4x10¹⁰ Msun)
➔ ~1000 halos with $V_c > 20$ km/s (M>1.4x10⁹ Msun)

* Assuming that a galaxy of M = -16.5 inhabits a halo of 5x10¹⁰ Msun, the expected avg. number of galaxies brighter than -16.5 in a void of 14 Mpc radius is ~5.
*Gao, Springel & White (2005) found that the clustering properties of DM halos can depend strongly on their formation redshift (= by which half of its $z=0$ mass was assembled)

- Wechsler et al (2006) showed that halo concentration and subhalo occupation number et al are strongly correlated with formation redshift.
- Croton, Gao & White (2007) report that the clustering of DM halos depends not only on their mass but also on their assembly history

⇒ “Assembly Bias”

- How can Assembly Bias affect Void populations?
  - Assembly bias is seen to be stronger in lower mass halos; since low mass halos form later in underdense regions, z-dependence of the background UV flux will impact differently gas accretion and SF processes, than it would in different cosmic density regimes. Also note that the IGM density will presumably be lower in voids, which will affect the gas accretion rate by galaxies.
Hoeft et al. (2006) simulated the SF processes in voids, using code that included radiative processes, SN feedback and an external, photoionizing Hardt & Madau (1996) UV background, with a resolution that allows monitoring evolution of DM halos of mass as low as 2.3x10^8 Msun.

As Gottloeber et al did before, they find voids filled with halos of M<10^{10} Msun. If each of those retained its share of the cosmic baryon fraction and converted it into stars without significant suppression of gas cooling, a high density of luminous dwarfs should be expected in dwarfs.

However, small halos DO NOT retain their share of baryons

- Note dependence on simulation resolution!

Characteristic halo Mass $M_c$ : that which retains 50% of its baryons
-Hoeft et al 2006 (cont.):

- The retained baryon fraction depends on the UV background flux
  (low UV = x0.01  high UV = x100)

- The UV background heats the gas to \( \sim 10^4 \) K
- In order for the gas to be accreted, cool and form stars, the halo \( T_{\text{vir}} \) must be at least \( \sim 10^4 \) K:
  \[
  T_{\text{vir}} \sim 10^4 \text{ K} \Rightarrow M_{\text{halo}} \sim 2 \times 10^9 \text{ Msun at } z=0
  \]

  In halos less massive than \( \sim \), the baryons stay warm and are not accreted.

- But see: Sternberg, McKee & Wolfire (2002) coming up later...
WSRT observations

- Nice, regular HI distribution. Some rotation??????
- HI velocity matches optical velocity: 39 vs 38 km s\(^{-1}\)
- Velocity dispersion HI: 7 km s\(^{-1}\), stars 8 km s\(^{-1}\)
- \(M_{\text{dyn}}/L_V \sim 125\)

Credit: T. Osterloo, Spineto 2007

Ricotti (2009): minihalos form early and grow accreting DM and baryons until the IGM is fully ionized after EOR; then the Jeans' mass in the IGM becomes > minihalo mass; gas accretion stops, DM accretion continues; after a while, gas accretion resumes and SF is possible again.

HI mass = 3\times10^5 M_{\odot}
HIMass/L_V = 5
M_{\text{dyn}}=8\times10^6 M_{\odot}
... and still forming stars...
[80% of visible baryons in HI]
* Halo Occupation Distribution (HOD) is a technique used to interpret galaxy clustering. In populating halos with galaxies it assumes that the assembly history of a halo of given mass – and thus in delivering its galaxy content – is independent on the large-scale environment.

- Gao & White (2007) have shown how the Assembly Bias affects several characteristics of a halo: formation time, concentration, subhalo mass fraction, spin. Assembly bias can therefore affect the predictions based on HOD, which assumes that a halo doesn’t know whether it sits in a void or a filament, i.e. that its galaxy properties depend only on the halo mass.

However

- Tinker et al. (2008) tested HOV and find that – at least for galaxies brighter than ~0.2L* - HOD is a satisfactory approach.
- Tinker & Conroy (2008) used HOD to show that there is no Void Problem.
Tinker & Conroy (2009) use a high resolution DM simulation, which they populate with galaxies via the HOD process. Galaxies of a wide range of \( L \) equally outline the voids

\[ \text{[blue=-14/-15 green=-16/-17 red=-18/-19]} \]

\[ M_r = -21 \]

Maximum halo mass found within distance \( R \) from center of void

“Characteristic Mass” of Hoeft et al (2006): mass within which retained baryon fraction is \( \frac{1}{2} \) of cosmological value (0.16)
So is the “Void Problem” solved?
Sternberg, McKee & Wolfire (2002) have investigated the gastrophysics of minihalos: the remaining baryons in a low mass halo are capable of developing a small WARM NEUTRAL phase (WNM), possibly detectable through its HI emission.

Do we have any chances to ever observe these guys?
A possible model for a baryon-poor minihalo:

\[
M_{\text{halo}} = 3 \times 10^8 M_{\odot}
\]
\[
M_{\text{baryon}} = 5 \times 10^6 M_{\odot}
\]
\[
M_{HI} = 3 \times 10^5 M_{\odot}
\]
\[
R_{HI} = 0.7 \text{kpc}
\]
HVCs: an Intergalactic Population?

Blitz et al (1999): HVCs are large clouds, with typical diameters of 25 kpc, containing $3 \times 10^7$ solar of neutral gas and $3 \times 10^8$ solar of dark matter, falling towards [the barycenter of] the Local Group; altogether the HVCs contain $10^{10}$ solar of neutral gas.

Braun & Burton (1999): The "undisturbed minihalos appear as Compact HVCs, which have typical sizes of 0.5 deg and FWHM linewidts 20-40 km/s

Problems:

If HVCs (or CHVCs) are bona fide LG members, they should also exist in galaxy groups other than the LG: NOT SEEN

2. Sternberg et al (2002) show that, in order to fit DM halo models to the CHVCs, their HI fluxes and angular sizes objects them to be no farther than 150 kpc, else they famously violate the $\Lambda$CDM mass-concentration relation: CHVCs ARE TOO LARGE

⇒ Enter ALFALFA
HVCs in footprint of ALFALFA, North Galactic Cap

$\Omega = 1620 \text{ sq deg}$

LG galaxies within $D=2.6$ Mpc (away from center of LG)
ALFALFA region maps onto Karachentsev et al catalog as shown above in red and onto HVC sky distribution as shown in next image.
22 very compact HVCs are found in the ALFALFA region... they are good baryonic counterparts to minihalo candidates

Map rms: 3.40824 mJy/beam
Positive Contours: 1 through 20 times rms
Negative Contours: −2 and −1 times rms
ALFALFA Minihalo Candidates at d=1 Mpc

- Mean HI Mass: $3 \times 10^5$ solar
- Mean HI Diameter: 0.7 kpc
- Mean avged HI column density: $10^{19.1}$ cm$^{-2}$
- Mean avged HI density: 0.006 cm$^{-3}$
- Mean total mass within $R_{HI}$: $3 \times 10^7$ solar

Sternberg et al (2002) Minihalo Template @ P=10 cm$^{-3}$ K

- HI Mass: $3 \times 10^5$ solar
- HI Diameter: 0.7 kpc
- Peak HI column density: $10^{19.6}$ cm$^{-2}$
- WIM Mass: $6 \times 10^6$ solar
- Total mass within $R_{vir}$: $3 \times 10^8$ solar

At the distance of nearby groups of galaxies, the ALFALFA minihalo candidates would have been below the sensitivity limit of extant HI surveys.
We have found a subset of the HVC phenomenon that appears to be compatible with the LG minihalo hypothesis. Other interpretations are possible, we have not proved that the candidates are LG minihalos, but that is a tantalizing possibility.

However....
What is this:?
- A very anomalous HVC?
- RFI?
- Extragalactic??

Half a Degree away we find.....

\[ V_{helio} = 386 \text{ km/s} \]
\[ W_{50} = 10 \text{ km/s} \]
\[ M_{HI} = 4.7 \times 10^4 D^2 M_{\odot} \]

V_LG~300

HI feature with no optical counterpart
Half degree away from cloud, another HI source is found with similar vel; this one however has optical counterpart with matching optical redshift...