Intergalactic baryon-rich regions at high redshift

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ABSTRACT

Using a high-resolution cosmological simulation of reionization, we have examined the differing structures formed by gas and dark matter at a redshift of 5.1. Baryon-rich regions form a small number of filaments, which connect the largest galaxies in the simulation. More detailed examination of the 10 largest galaxies reveals long, slender gaseous filaments about five proper kpc in width radiating from the galaxy centers. Extending out from each filament are a few smooth, thin, nearly planar gaseous sheets. By contrast, the dark matter concentrates into quasi-spherical bodies. The results have implications for our understanding of structure formation in the early Universe and of the Lyman α forest.

Key words: galaxies: high-redshift – intergalactic medium – cosmology: theory – dark matter – large scale structure of Universe.

1 INTRODUCTION

During the first gigayear of the Universe, the first stars, galaxies and black holes formed, and reionization was completed. Most of the matter resided in the intergalactic medium, forming a network of sheets and filaments (for reviews see Barkana & Loeb 2007 and Meiksin 2007). In this environment, galaxies grew by accreting dark matter and gas to form the ‘cosmic web’ of walls and filaments of clusters of galaxies that characterize the visible large-scale structure of the universe today.

Gravitational clustering produces sheets and filaments naturally, because gravitational collapse of ellipsoidal maxima occurs at different times along the three unequal axes (Lin et al. 1965; Ze’ldovich 1970; Jing & Suto 2002; Shen et al. 2006). Collapse occurs first along a single axis to produce a two-dimensional sheet. Subsequent collapse of a sheet along a second axis produces a filament. Finally, collapse of filaments leads to quasi-spherical galactic haloes. Because matter clusters at various scales and with a range of overdensities, all three kinds of structure may coexist at a single moment in time. Cosmological simulations using a variety of cosmological models confirm that sheets and filaments occur generically and ubiquitously (for discussion, see Shandarin et al. 1995; Bond, Kofman & Pogosyan 1996; Valinia et al. 1997; Schmalzing et al. 1999; Sheth et al. 2003 and Shen et al. 2006; for reviews of early theoretical work see Shandarin, Doroshkevich & Ze’ldovich 1983 and Shandarin & Ze’ldovich 1989).

At large scales, baryons and dark matter are expected to trace the same structures. Cosmological hydrodynamic simulations with resolutions in the tens of kiloparsecs have borne this out, although differences in the smoothness of the gas and dark matter have been noted (Cen et al. 1994; Hernquist et al. 1996; Miralda-Escudé et al. 1996; Zhang et al. 1998).

On smaller scales, hydrodynamic processes may be expected to lead to some separation of baryons and dark matter. The purpose of this paper is to explore this separation using a cosmological simulation that has subkiloparsec resolution and includes a detailed and careful treatment of baryonic physics (Harford & Gnedin 2007). The simulation includes three-dimensional radiative transfer of radiation produced self-consistently by star formation, and it follows the detailed ionization and chemistry of atomic hydrogen, molecular hydrogen and helium. We focus on an epoch at high redshift following reionization. The Jeans length changes by more than an order of magnitude over the course of reionization (see Gnedin et al. 2003, and references therein).

The simulation method has been validated in several respects. First, galaxy luminosity functions compare favourably to observations (Harford & Gnedin 2003, 2007.). Secondly, the reionization history is consistent with the spectra of high-redshift quasars (Gnedin & Fan 2006). Finally, considerable progress has been made in reproducing the frequency of Lyman limit systems (Kohler & Gnedin 2007).

In examining the output of the simulation reported here, we were struck by the marked difference in the distribution of baryons and dark matter on scales small enough that hydrodynamic processes are important, but large enough that intergalactic structure is easily visible. We noted that intergalactic gas tends to occur in long, nearly continuous filaments and attached sheets, which are unusually rich in baryons relative to the cosmic mean. These filaments form ‘backbones’ to which large, dark matter dominated galaxies

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2 THE SIMULATION

The simulation used in this paper was run with a ‘Softened Lagrangian Hydrodynamics’ (SLH-P3M) code (Gnedin 1995; Gnedin & Bertschinger 1996). The simulation has a flat Λ cold dark matter (ΛCDM) cosmology, with values of cosmological parameters determined by the first year Wilkinson Microwave Anisotropy Probe (WMAP) data (Spergel et al. 2003): \( \Omega_m = 0.27, \Omega_b = 0.04, \sigma_8 = 0.91 \) and \( h = 0.71 \). The mean baryonic fraction is therefore 0.148. We focus on an epoch at redshift 5.135. The computational expense to run this simulation to significantly later times is prohibitive.

Each dimension of the simulation box is \( 8h^{-1}\) Mpc comoving, and contains 256 Lagrangian simulation cells. The gas dynamics is followed on a quasi-Lagrangian mesh, which is gradually deformed during the simulation to achieve better resolution in high-density regions. In the post-processing stage, in order to compare dark matter and baryons in a similar manner, we convert each cell of the quasi-Lagrangian mesh into a ‘gas particle’ with the same physical properties (mass, momentum, temperature, etc.). The positions of an equal number of dark matter particles of constant mass \( 2.73 \times 10^6 \, M_\odot \) are computed with the P3M algorithm using a softening length of 0.08 kpc proper. The best resolution is limited to about two to three times the softening length.

The reionization process is simulated by including star formation by the Schmidt law and radiative transfer by the optically thin variable Eddington tensor method (OTVET) (Gnedin & Abel 2001). Also included are the radiative transfer effects of molecular hydrogen, whose formation and disassociation are followed. A two-level implicit scheme is used to compute the effects of a hydrogen and helium plasma.

We analyse the simulation on a grid with cell size of 40 kpc comoving (28.4 kpc proper at a redshift of 5.135). This cell size is about 80 times the softening length. This choice of grid cell size, comparable to the size of a small galaxy, is a deliberate one. The grid cell size is small enough to bring out the separation of baryons and dark matter produced by hydrodynamical processes, but large enough to map regions of overdensity as low as \( 10^{1.75} \), about 56, with good signal-to-noise ratio. We find this overdensity to be a convenient lower limit to differentiate the filamentary structure. Results for other grid cell sizes and other redshifts are explored in an Appendix.

The spatial resolution at any point in the simulation depends upon the local density of the Lagrangian simulation cells, which is roughly proportional to the local overdensity. However, the proportionality breaks down in regions of very high or low baryonic fraction. We have determined that all of the baryon-enriched grid cells with a minimum overdensity of 56 at \( z = 5.1 \) have a minimum of 60 gas particles, each of which corresponds to a cell of the simulation. The unenriched grid cells may have fewer gas particles, and consequently lower resolution.

Unless otherwise noted all distances in this paper are proper.

3 BARYON-RICH FILAMENT

The upper panel of Fig. 1 illustrates how the baryon-rich regions in the simulation form a network of filaments. The baryon-rich regions, plotted in translucent green, are grid cells whose total overdensity is at least 56, and whose baryon fraction is at least twice the cosmic mean. Both gas and stellar matter in the simulation are included as baryons in this paper. The stellar mass in a region is usually much less than the gas mass, and generally we have not examined it separately.

The baryon-rich filaments are associated with the largest galaxies in the simulation. The upper panel of Fig. 1 shows, as black spheres, the 88 largest galaxies in the simulation, those with a total mass of at least \( 10^{10} \, M_\odot \) in dark matter and baryons. Galaxies were identified with the \textsc{denmax} algorithm (Bertschinger & Gelb 1991) as gravitationally bound density peaks containing at least 100 simulation particles. The most massive galaxy in the simulation is \( 1.2 \times 10^{11} \, M_\odot \).
Fig. 2 shows how many galaxies in each mass range are within two grid cells of a baryon-rich cell (we define such cells as ‘nearby’ hereafter). Above a mass of $10^{10} \, M_\odot$, 83 per cent of the galaxies are nearby, while below this range only 11 per cent are. The nearby galaxies account for 85 per cent of the galactic stellar mass. Because many of the smaller galaxies are devoid of stars, only 38 per cent of the galactic dark matter is nearby.

Although the largest galaxies in the simulation are near the baryon-rich filaments, the galaxies themselves generally have baryonic fractions close to the cosmic mean.

The baryon-rich regions are relatively rare compared to unenriched regions. The lower panel of Fig. 1 shows unenriched cells with an overdensity of 56 or greater. The unenriched cells outnumber the enriched cells by a factor of about 20. The unenriched regions, though clustered, are not as strikingly filamentary as the enriched regions.

Fig. 3 shows that baryon-rich cells constitute about 1/20th of the volume of unenriched cells, almost independent of overdensity. The figure shows only overdensities 56 or above because the determination of baryon fraction becomes increasingly uncertain at lower overdensities. The figure suggests a slight trend for greater enrichment at lower overdensity, but the statistical significance is not large.

Fig. 4 shows a zoom-in of the longest enriched filament in Fig. 1. The zoom-in shows large galaxies as clumps of unenriched grid cells arranged along a baryon-rich backbone. The lower panel of the figure shows the backbone by itself, with gaps at the positions of some of the large galaxies. We expect galaxies to concentrate gas at their centers, and many in the simulation do. However, the central regions are usually too small to show up as baryon-rich on the adopted 6.5 kpc grid scale.
Baryon-rich structures

Figure 5. Upper panel: gas simulation particles in a small region of the filament that is shown in Fig. 4. Lower panel: same view showing just dark matter particles. The width of the images is about 200 kpc.

Fig. 5 zooms in still further to show individual simulation particles. The upper panel shows just the gas particles concentrated into filaments. The lower panel shows the same field of view with just the dark matter particles. The dark matter, although broadly following the filaments, tends to assume quasi-spherical shapes.

4 FILAMENTS RADIATE FROM CENTERS OF GALAXIES

In Section 3, we showed that the baryon-rich regions of the simulation form a system of filaments that connect the largest galaxies. In this section, we explore the properties of the filaments in more detail by focusing on regions surrounding the 10 largest galaxies and the second largest galaxy in particular.

Fig. 6 shows four images of a 55.4 kpc (proper) radius region centered on the second largest galaxy. The two upper images show the gas particles (left-hand side) and dark matter particles (right-hand side) which are bound to the galaxy as indicated by DENMAX. Each lower image shows the corresponding unbound particles. The three major spokes of bound gas in the upper left-hand side image are nearly coplanar.

To isolate individual filaments for quantitative study, we examine a shell extending from 22.2 to 55.4 kpc around each of the 10 largest galaxies. The inner radius encompasses the bound region of the galaxy, while the outer radius is large enough to reveal the filamentary structure clearly, but not so large as to encroach on neighbouring large galaxies. On average, 10 per cent of the solid angle of the shell contains 65 per cent of the gas and 50 per cent of the dark matter.

Fig. 7 shows contour maps of a 192-pixel HEALPix1 tiling (Górski et al. 2005) of the shell around the galaxy in Fig. 6. The dark matter (top panel) shows the smoothest distribution, while gas, neutral hydrogen and stars (succeeding panels) are progressively more concentrated.

For objectivity, we adopted a simple formal procedure for selecting the peak pixels that define the filaments. First, we select those pixels that contain at least \(3.6 \times 10^8\) M\(_\odot\) of gas. This minimum mass requirement is imposed so that a radial segmentation of a pixel into six equal parts is expected to contain at least \(6 \times 10^7\) M\(_\odot\) of gas, which is more than one hundred times the fiducial mass of a gas particle in the simulation. Some smaller filaments, apparent to the eye, are thus omitted. Having made this selection, we refer to the contour maps to ensure that only 1 pixel, the maximum, is chosen from each contour peak. This procedure yields a total of 29 filaments around the 10 galaxies. Two of the 29 filaments overlap along their length, but the overlap is only about 30 per cent of the length analysed.

Fig. 8 shows that the linear mass density of gas in the filaments generally varies along the filament by less than a factor of 2 or

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1 We gratefully acknowledge the use of the HEALPix software package obtained from http://healpix.jpl.nasa.gov.
Figure 7. Angular distribution of matter about the second largest galaxy, in Hammer–Aitoff projection. In descending order, the maps show dark matter, gas, neutral hydrogen and stars. The shown are contours of masses in the solid angles subtended by 192 HEALPix pixels for a shell from 22.2 to 55.4 kpc. For each map, there are six contour levels with a factor of 2 spacing. The highest contour for each map is one-half the maximum of that map.

3. The range of values among the filaments is about an order of magnitude, with a few outliers. The figure shows the mean density in cylinders of radius 8 and 16 kpc about a radial axis centered on the peak pixel.

Figure 8. Linear density of gas along each of the 29 filaments around the 10 largest galaxies. Each curve represents one filament, and each point represents the gas contained in a segment of a coaxial cylinder around that filament of radius 8 kpc (left-hand panel) or 16 kpc (right-hand panel). See Fig. 12 for a drawing of the geometry. The abscissa is distance from the galaxy center along the filament. The points are plotted at the centers of the segments.

Figure 9. Average cross-sectional profiles of filaments at each of three distances from the galaxy. The left- and right-hand panels show, respectively, the gas density and baryonic fraction as a function of distance from the center of the filament. In the right-hand panel, the black curves with the black-filled circles show the baryonic fraction in the individual radial bins, while the orange curves with the triangles show cumulative baryonic fractions for regions extending outward and including the bin. The green arrow in the right-hand graph shows the cosmic mean baryon fraction. For these graphs, each filament from 22.2 to 55.4 kpc from the center of the galaxy was divided into three equal segments. Solid, dotted and dashed lines show profiles for the inner, middle and outer segments averaged over all 29 filaments. Gas densities and baryonic fractions were computed on cylindrical shells having a radial width of 2 kpc. In the left-hand panel, the data for each filament segment were normalized to the gas density in the lowest radial bin for that particular filament. Vertical lines show 2σ errors. Symbols are plotted at the centers of the radial distance bins.

Fig. 9 shows further evidence that the properties of filaments do not vary greatly along their length. The figure shows that the average cross-sectional profile of gas density and baryonic fraction of filaments is approximately independent of distance from the galaxy. Each of the three black curves with filled circles in each graph shows the profile, averaged over all 29 filaments, of one of three equal segments spanning the distance from 22.2 to 55.4 kpc from the galaxy.

The lower panel of Fig. 9 shows that the average baryonic fraction (black curves with filled circles) exceeds twice the cosmic mean out to about 5 kpc, and remains above the cosmic mean out to about 9 kpc, beyond which it dips slightly below the mean. This is consistent with the idea that there has been a separation of baryons and dark matter, with baryons becoming more centrally concentrated in the filaments. The figure also shows the cumulative baryonic fraction (orange curves with triangles) within the radius. The cumulative baryonic fraction remains elevated out to beyond 20 kpc. At least some of this enhanced baryon fraction can be attributed...
to sheets, described in the next section, at whose intersections the filaments are found.

5 FILAMENT-ASSOCIATED SHEETS

Radiating from the filaments are thin sheets of gas. Fig. 10 shows three sheets extending from a single filament of the galaxy shown in Fig. 6. The images on the left-hand panel show gas particles, and those on the right-hand panel show dark matter particles. The top panel shows a projection on to a plane perpendicular to the filament, with the filament in the center. The top left-hand side image shows the three sheets edge-on. The lower left-hand side image shows this complex from another angle so that the three sheets are fully visible. The filament lies at the intersection of the three sheets. Outlines of a surrounding box are shown to enhance the three-dimensional effect. The filament is perpendicular to the front face of this box. The image on the lower right-hand side shows the same view as on the left-hand side but with dark matter particles only. There is some tendency for the dark matter to concentrate in the vicinity of the sheets, but it tends to form quasi-spherical haloes rather than the thin, extended sheets formed by the gas.

Fig. 11, a montage of images of the remaining 10 filaments from the three largest galaxies (omitting the one shown in Fig. 10), gives an idea of the variation seen. Each image is a view centered on a single filament running perpendicular to the page. The images are arranged in horizontal pairs with the gas particles shown on the left-hand side and the dark matter particles on the right-hand side. The spokes of gas radiating from the filament are the sheets seen edge-on. Viewed face on, the sheets resemble those in the image in

Figure 10. Sheets of gas radiating from a filament. Shown is the distribution of gas and dark matter around the axis of a filament from the galaxy shown in Fig. 6. Upper panel shows gas particles (left-hand panel) and dark matter particles (right-hand panel) in a projection on to a plane perpendicular to the filament. The axis of the filament is at the center going into the page. In the lower panel, these structures are shown at a different angle to show the three sheets formed by the gas particles (left-hand panel) and the more irregular distribution of the dark matter particles (right-hand panel). The dimension of each square image, and of the box, is 110.8 kpc proper.

Figure 11. Sheets of gas radiating from the other filaments around the three largest galaxies. Each horizontal pair of images represents the same filament with the gas particles on the left-hand panel and the dark particles on the right-hand panel. Each filament is viewed as a projection on a plane perpendicular to the filament with the filament in the center going into the page. Each image is 110.8 kpc on a side. Only the portion along the filament from 22.2 to 55.4 kpc from the center of the galaxy is shown.

Figure 12. Cutaway of analysed regions surrounding a galaxy. The solid vertical line represents a filament extending 55.4 kpc from the center of a galaxy at its lower end. The dashed black lines show the shell about the galaxy that contributes to the HEALPix contour map. Linear density along the filament is computed for the 8 kpc orange cylinder. The green wedge portrays one of the 16 radial sectors used to select the sheets. The red-dotted box depicts a slab centered on a selected sheet.

To quantify the gas density and baryonic fraction of the sheets, we averaged over rectangular slabs whose geometry and selection is diagrammed in Fig. 12. To select sheets, we take a cylinder of radius 55.4 kpc coaxial with each filament, and divide it into 16 equal angular sectors. We exclude from the volume analysed an inner cylinder of radius 8 kpc to eliminate the central region of the filament itself. We select as a sheet those sectors that contain at

the lower left section of Fig. 10. Although dark matter clusters near the sheets, it is more diffusely distributed than the gas.

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2 Spearman’s rho for rank correlation is 0.53, which for a two-tailed distribution is significant at the 95 per cent level. To compute this, sheets attached to the same filament were averaged, resulting in 15 pairs for rank order analysis.

6 DISCUSSION AND CONCLUSIONS

Using a high-resolution cosmological simulation of reionization, we have found evidence for a significant population of baryon-rich filaments at a redshift of 5.1. The filaments are associated with the largest galaxies, and can be found radiating away from their centres. The baryon-rich filaments are at the intersections of sheets, which also tend to be enriched in baryons. The dark matter is distributed more irregularly, tending to form quasi-spherical bodies.

This work helps to fill a somewhat neglected gap between the linear regime of gravitational collapse and the highly non-linear regime of galactic interiors. Our investigation has highlighted the contrasting distribution of baryons and dark matter on ∼6 kpc scales where hydrodynamic processes are important, but intergalactic structure is still readily delineated. The simulation investigated in this paper was originally carried out in order to explore reionization, and therefore includes detailed baryonic physics, including three-dimensional radiative transfer of ionizing radiation self-consistently generated by star formation, that is often neglected in other kinds of cosmological simulation. The results point to a need for careful treatment of baryonic processes in modelling moderately non-linear scales.

At large, linear scales, baryons and dark matter are expected to follow the same distribution. In the opposite limit of small, highly non-linear scales, the baryonic fraction within the virial radius of a collapsed halo is close to the mean (Crain et al. 2007). It may therefore seem surprising that at intermediate, mildly non-linear scales, the difference between the distribution of baryons and dark matter can be as prominent as found in this paper. Linear theory predicts that initially the difference in the clustering of baryons and dark matter is described by a filtering scale (Gnedin & Hui 1998), below which pressure forces tend to smooth the baryons compared to the dark matter. The present simulation indicates that, at least in regions where the separation of baryons and dark matter is most marked, the separation is more complex, and anisotropic. Baryons tend to concentrate towards the centers of filaments and sheets, in directions perpendicular to the filament or sheet, but are more smoothly distributed than dark matter in directions along the filament or sheet. The central concentration of baryons compared to dark matter is consistent with simple models of one-dimensional linear theory.

A selection process produced 32 sheets from the 29 filaments around the 10 largest galaxies. The central concentration of baryons compared to dark matter is consistent with simple models of one-dimensional collapse into filaments and sheets (Shandarin & Zel’dovich 1989; Anninos, Norman & Anninos 1995) although this consistency is perhaps surprising given that evolution is much more complicated in three dimensions than in one. Another unexpected finding is that the baryon-rich filaments and sheets remain coherent over scales much larger than the filtering scale of 4 kpc proper (24 kpc comoving) predicted at this redshift by Gnedin et al. (2003).

Undoubtedly, much of the difference between baryons and dark matter in the simulation reported in this paper can be attributed to the fact that baryons are collisional whereas dark matter is collisionless: parcels of collapsing gas cannot pass through each other, whereas dark matter can. Probably another important effect is that the energy of collapse of the baryons into filaments and sheets is channelled into gas pressure, mediated at least in part by coaxial shocks, as suggested by Cen et al. (1994), Miralda-Escudé et al. (1996) and Zhang et al. (1998), which can smooth the baryons in directions along the filaments and sheets.

The baryon-rich filaments may have important implications for our understanding of structure formation in the universe. First, charting the course of reionization depends heavily upon uncertain assumptions about the escape fraction of ionizing radiation from galaxies. The highly aspherical distribution of the surrounding gas should be taken into account in mapping the journey of...
such a photon from its origin near the center of the galactic halo. In this regard, it is interesting that the filaments appear to extend essentially unaltered into nearly the center of the galaxy.

Secondly, the filaments are likely to be important in the process of gas accretion on to galaxies. As discussed by (Kereš et al. 2005, and references therein), two general modes of accretion are distinguished, a hot mode and a cold mode. In the hot mode, which dominates the growth of the largest galaxies, gas, shock heated to the virial temperature of the dark matter halo, accretes in a spherically symmetric fashion. In the cold mode, which dominates for smaller galaxies, such as those seen in our simulation, gas accretes in a directional manner, often along filaments (Kawata & Rauch 2007). The filaments we see are obvious candidates for cold accretion conduits. Since the ability of a galaxy to accrete gas is important for sustained star formation, the evolution of these structures may, in turn, help us to understand the star formation history of the Universe.

Thirdly, the planar distribution of Milky Way satellite galaxies may have resulted from an early sheet (Libeskind et al. 2005), possibly of the kind described in this paper.

The baryon-rich structures discussed in this paper may be potentially observable in the Lyman α forest (for reviews see Rauch 1998; Meiksin 2007), although a precise assessment of their observational impact will require further work that goes beyond the scope of this paper. Descendants of these structures may play a role in producing the warm-hot intergalactic medium (WHIM), thought to be a major reservoir of baryons in the low-redshift Universe (Davé et al. 2001).

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APPENDIX A: VARYING CELL SIZE AND REDSHIFT

Fig. A1 shows the volume fractions enriched in baryons for grid cell sizes of 4.1 and 16.3 kpc proper (25 and 100 kpc comoving) at a redshift of 5.1. These graphs are to be compared to Fig. 3, which shows the results for the 6.52 kpc (40 kpc comoving) cell size used predominantly in the paper. The results for a grid cell size of 4.1 kpc are consistent with those at 6.52 kpc. We preferred the larger cell size because estimates of the baryon fraction in each cell are more accurate, especially at lower overdensities. Increasing the cell size to 16.3 kpc leads to a considerable loss of baryon-rich cells. This is consistent with the ~5 kpc radius of filaments illustrated in Fig. 9.

Figure A1. Effect on baryonic fraction of varying the grid cell size. Same as Fig. 3, but for cell sizes of 4.1 kpc proper (25 kpc comoving) in the upper graph, and 16.3 kpc proper (100 kpc comoving) in the lower graph.
Fig. A2 compares the baryon-rich fraction over a range of redshifts (the data for $z = 4$ were obtained from a lower resolution simulation). The baryonic enrichment appears generally to increase with time. Computational limitations prevent us from evolving the simulation to lower redshifts.

**Figure A2.** Volume fraction of baryon-enriched regions as a function of overdensity, at several redshifts. As elsewhere in this paper, the threshold for baryon enrichment is taken to be twice the cosmic mean. The cell size for all redshifts is 40 kpc comoving. Vertical lines show $2\sigma$ errors (only the upper errorbars are shown).