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Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY LETTERS

Mon. Not. R. Astron. Soc. **413,** L51–L55 (2011) doi:10.1111/j.1745-3933.2011.01031.x

Are cold flows detectable with metal absorption lines?

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Accepted 2011 February 16. Received 2011 February 4; in original form 2010 November 30

ABSTRACT

Cosmological simulations have shown that dark matter haloes are connected to each other by large-scale filamentary structures. Cold gas flowing within this 'cosmic web' is believed to be an important source of fuel for star formation at high redshift. However, the presence of such filamentary gas has never been observationally confirmed despite the fact that its covering fraction within massive haloes at high redshift is predicted to be significant (∼25 per cent). In this Letter, we investigate in detail whether such cold gas is detectable using low-ionization metal absorption lines, such as C II λ1334, as this technique has a proven observational record for detecting gaseous structures. Using a large statistical sample of galaxies from the MareNostrum N-body+ adaptive mesh refinement (AMR) cosmological simulation, we find that the typical covering fraction of the dense, cold gas in 10^{12} $M_{\odot}$ haloes at $z \sim 2.5$ is lower than expected (∼5 per cent). In addition, the absorption signal by the interstellar medium of the galaxy itself turns out to be so deep and so broad in velocity space that it completely drowns that of the filamentary gas. A detectable signal might be obtained from a cold filament exactly aligned with the line of sight, but this configuration is so unlikely that it would require surveying an overwhelmingly large number of candidate galaxies to tease it out. Finally, the predicted metallicity of the cold gas in filaments is extremely low ($\lesssim 10^{-3}$ $Z_{\odot}$). If this result persists when higher resolution runs are performed, it would significantly increase the difficulty of detecting filamentary gas inflows using metal lines. However, even if we assume that filaments are enriched to $Z_{\odot}$, the absorption signal that we compute is still weak. We are therefore led to conclude that it is extremely difficult to observationally prove or disprove the presence of cold filaments as the favourite accretion mode of galaxies using low-ionization metal absorption lines. The Lyα emission route looks more promising but due to the resonant nature of the line, radiative transfer simulations are required to fully characterize the observed signal.

Key words: galaxies: formation – galaxies: high-redshift – galaxies: intergalactic medium – cosmology: theory.

1 INTRODUCTION

How galaxies get their gas is a longstanding issue. For decades, the standard theoretical picture of galaxy formation has stipulated that all gas accreted into dark matter haloes is shock heated before it radiatively cools and settles into a galactic disc (Silk 1977; Rees & Ostriker 1977, although Binney 1977 first suggested this need not be the case). This picture has recently been revisited by both analytic studies (Birnboim & Dekel 2003; Dekel & Birnboim 2006) and hydrodynamical simulations [both in one-dimension (Birnboim & Dekel 2003) and in three-dimensions within an explicit cosmological context (Kereš et al. 2005, 2009; Ocvirk, Pichon & Teyssier 2008, hereafter OPT08)]. These studies have established that in haloes below a critical mass shocks are unstable and cannot propagate outwards, so that cold diffuse gas and/or cold filaments can penetrate deep into the halo without experiencing shock-heating. In contrast, at the other end of the mass spectrum, very massive haloes easily sustain a virial shock that is stable against gas cooling so that diffuse/filamentary gas is shock heated to the virial temperature of the halo as it enters. Finally, at intermediate halo masses, either gravitationally shock-heated hot gas and/or a hot galactic wind coexist with cold inflowing filaments (OPT08): some dense cold filaments are stable against the pressure force exerted by the hot gaseous material. In other words, the vast majority of galaxy-sized host haloes, especially at high redshift ($z > 2$), are predicted to be

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threaded by cold gas filaments in a Λ cold dark matter model of structure formation. Therefore, the question which naturally arises is whether or not the existence of these cold gas filaments can be observationally confirmed, and by which technique.

Since the advent of high-resolution spectroscopy has enabled astronomers to study the kinematics of the intergalactic medium at high redshifts in a great details (e.g. Pettini et al. 2002; Adelberger et al. 2003; Shapley et al. 2003), and given the fact that cold gas is thought to flow into massive haloes ($10^{12}\,M_\odot$) at $z = 2.5$ along filaments with velocities of $\gtrsim 200\,\mathrm{km\,s^{-1}}$ (Dekel et al. 2009), it is sensible to think that the spectra of Lyman-break galaxies (LBG; Steidel et al. 1996) might reveal these filaments as redshifted absorption features. Interestingly, a recent study reported that few LBGs show redshifted metal absorption lines, suggesting that inflowing gas in haloes with $4 \times 10^{11} < M_{\rm vir} < 10^{12}\,M_\odot$ is rare (Steidel et al. 2010). Taken at face value, this appears to contradict the theoretical prediction that cold filaments are prominent in the vast majority of high-z haloes.

However, there exist a variety of reasons as to why these filaments should be very difficult to detect. The first of these is the covering fraction of the filaments. This is estimated in Dekel et al. (2009) to be around (∼25 per cent) for four massive haloes with $M_{\rm vir} \sim 10^{12}\,M_\odot$ in the Horizon-MareNostrum simulation, counting only relatively dense ($N_{\rm H} > 10^{20}\,\mathrm{cm^{-2}}$) and cold ($T < 10^5$ K) gas within a radial distance $20 < r < 100$ kpc from the central galaxy hosted by these haloes. Whereas 25 per cent is indeed a non-negligible covering fraction, its exact dependence on redshift and halo mass remains to be determined. For instance, Faucher-Giguére & Kereš (2011) also measured the covering fraction for a Milky Way type progenitor LBG in a smoothed particle hydrodynamic simulation but found a significantly smaller value (∼2 per cent). Secondly, low-ionization lines can be produced not only by cold filamentary gas but also by a galaxy's interstellar medium (ISM), so that when using a single galaxy to probe the circumgalactic medium, distinguishing absorption produced by filaments from that produced by the ISM is the key to prove/disprove the presence of cold filaments. Thirdly, there is the geometry of the accretion: in order to produce a strong absorption signal, a filament needs to be well aligned with the line of sight to maximize its column density. Finally, there is the issue of metallicity: a metal-poor filament will be transparent to metal line observations.

The aim of this Letter is to quantify the aforementioned effects to better assess the detectability of the absorption signal produced by cold filaments. We show that the actual probability of detecting such flows with metal lines is much smaller than the high covering fraction derived in Dekel et al. (2009) would suggest due to (i) the low density and (ii) low metallicity of the filaments *compared with the densities and metallicites of the ISM of the host galaxy.*

2 SIMULATIONS

To investigate the statistical properties of cold filaments, we analyse the Horizon-MareNostrum simulation, carried out with the 1-yr *Wilkinson Microwave Anisotropy Probe* (*WMAP*1) cosmology (Spergel et al. 2003) using the adaptive mesh refinement code ramses (Teyssier 2002). Details of the simulation can be found in OPT08, Dekel et al. (2009) and Devriendt et al. (2010), so we just briefly describe the simulation setup and modelling strategy here.

The simulation follows the evolution of a periodic cosmological volume of comoving side length $L = 50\,h^{-1}$ Mpc, and contains 1024^3 dark matter particles with $m_{\rm dm} = 1.4 \times 10^7\,M_\odot$. Dark matter haloes are identified using the AdaptaHop algorithm (Aubert, Pichon & Colombi 2004; Tweed et al. 2009), resulting in 3419 haloes with $M_{\rm vir} \geq 10^{11}\,M_\odot$ at $z = 3.8$ and 6456 haloes at $z = 1.5$. The spatial resolution of the simulation is kept fixed at around $1\,h^{-1}$ kpc physical over the entire redshift range.

Gas in the simulation can radiatively cool by atomic processes down to 10^4 K (Sutherland & Dopita 1993). A fraction of the cold and dense gas ($n_{\rm H} > 0.1\,\mathrm{cm^{-3}}$) turns into stars following the Schmidt–Kennicutt law (Kennicutt 1998), and massive stars explode as Type II supernovae, redistributing energy and metals into the interstellar/intergalactic medium. The Sedov Blast wave solution is adopted for supernova explosions (Dubois & Teyssier 2008), and reionization is implemented by instantaneously turning on a uniform UV background at $z = 8.5$ (Haardt & Madau 1996).

3 RESULTS

3.1 Covering fraction of dense gas

OPT08 showed that the transition mass ($M_{\rm stream}$) separating cold from hot dominated accretion increases with increasing redshift. According to these authors, by $z \sim 2.5$, the cold streams feeding massive haloes ($M_{200} \gtrsim 3 \times 10^{11}\,M_\odot$) begin to disappear, but based on measurements of a handful of haloes in the Horizon-MareNostrum simulation at $z \sim 2.5$, Dekel et al. (2009) find that some massive haloes with $M_{200} \sim 10^{12}\,M_\odot$ still show high covering fractions ($\lesssim$25 per cent) of dense ($N_{\rm H} > 10^{20}\,\mathrm{cm^{-2}}$) and cold ($T < 10^5$ K) inflowing gas within $20 < r < 100$ kpc. In order to obtain statistically significant results on the covering fraction in the Horizon-MareNostrum simulation, we analyse *all* the haloes in the simulation and show the results in Fig. 1. Using the complete sample, we find that the average covering fraction of haloes with $M_{200} \sim 10^{12}\,M_\odot$ at $z = 2.5$ is ∼5 per cent, about a factor of 5 less than the covering fraction reported in Dekel et al. (2009) for their sub-sample of $M_{200} \sim 10^{12}\,M_\odot$ haloes at $z \sim 2.5$. We note that this lower value is more consistent with the recent findings of

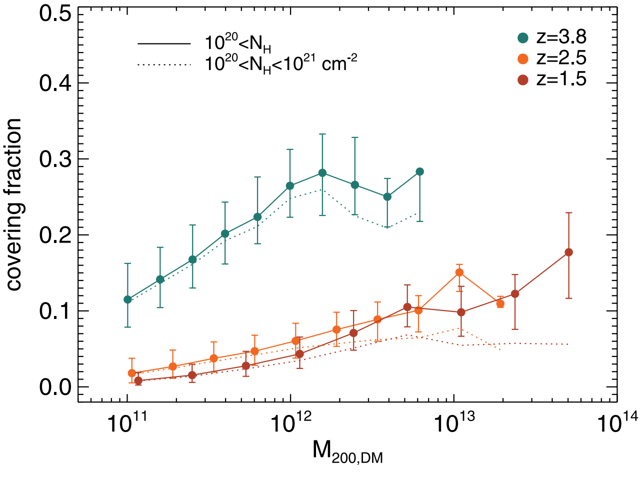

Figure 1. The covering fraction of cold ($T < 10^5$ K) and dense ($N_{\rm H} > 10^{20}$) gas within $20 < r < 100$ kpc physical as a function of the virial mass of haloes (M_{200}). Different colours indicate the covering fractions at different redshifts. Solid lines include the contribution from the ISM of satellite galaxies to the covering fraction. To exclude this latter contribution, we also plot the covering fraction with upper density cut ($10^{20} < N_{\rm H} < 10^{21}\,\mathrm{cm^{-2}}$, dotted lines). Error bars correspond to the interquartile range ($25 \leq f \leq 75$ per cent). For a given halo mass, haloes at higher redshift show larger covering fractions. This can be understood in terms of the rapid development of a virialized hot medium between $z = 3.8$ and 2.5.

Faucher-Giguére & Kereš (2011). However, whilst low covering fractions (∼5 per cent) are computed for most haloes at redshifts $z \lesssim 3$, those of higher redshift ($z \sim 3.8$) haloes are much larger (∼25 per cent), as can be seen in Fig. 1. This strong redshift evolution in the covering fraction of cold filaments between $z \sim 3.8$ and ~ 2.5 reflects the aforementioned rapid transition from cold to hot dominated accretion. We note that these results are consistent with the OPT08 value of $\sim 10^{13}\,\mathrm{M}_{\odot}$ for M_{stream} at $z = 4$.

An interesting feature present in Fig. 1 is that the covering fraction is higher in more massive haloes at a given redshift. This seems to contradict previous findings (OPT08) that the small haloes are mainly fed by cold mode accretion. It should be noted, however, that the covering fraction shown in Fig. 1 does not account for the accretion of cold, *diffuse* gas (cold gas with lower column densities) which is only present in haloes with masses incapable of sustaining a virial shock at all. Indeed, these small haloes are usually located within (or around) filaments whose density is low, whereas the filaments around more massive haloes tend to be denser. Furthermore, in massive haloes, satellite galaxies contribute more importantly to the covering fraction, as do extended, warped, galactic discs and dense gas bridges which result from tidal interactions between galaxies. These latter effects partly explain the trend, but the primary driver of the covering fraction increase with halo mass is the density of the accreted gas, which is higher in more massive haloes. Fig. 1 (dotted lines) substantiates this claim by showing how the covering fractions drop when the very dense gas ($N_{\mathrm{H}} > 10^{21}\,\mathrm{cm}^{-2}$) which belongs to the ISM of satellite galaxies is excluded from the measurement.

3.2 C II absorption

In order to more carefully investigate the possibility of detecting cold filaments using metal absorption lines, we compute the strength of the C II λ 1334 absorption. Our choice of line is dictated not only by the temperature of the filamentary gas which is not high enough to significantly produce more highly ionized metallic elements such as C IV, but also because it is empirically known to yield the strongest absorption feature (Steidel et al. 2010). We do not attempt to model absorption by C II accurately which would require detailed radiative transfer, but instead derive an upper limit by making several extreme assumptions. First, we assume that all the carbon present in filaments is eligible for the C II λ1334 transition. Secondly, we use the solar abundance ratio ($[\mathrm{C/Z}]_{\odot} \simeq 0.178$; Asplund et al. 2009) to obtain the carbon column density for a given metallicity in the simulation. The optical depth of a grid cell is computed as $\tau = \sigma_{\mathrm{C\,II}}\, n_{\mathrm{C\,II}}\, \Delta l$, where $n_{\mathrm{C\,II}}$ is the carbon number density, Δl is the size of the grid cell and $\sigma_{\mathrm{C\,II}}$ is the cross-section for the line transition, which is calculated as $\sigma_{\mathrm{C\,II}} = (3\pi\,\sigma_{\mathrm{T}}/8)^{1/2} f\,\lambda_0 \simeq 1.5 \times 10^{-18}\,\mathrm{cm}^2$. Here, σ_{T} is the Thomson cross-section, λ_0 is the rest-frame wavelength of the transition and f is the corresponding oscillator strength. We then correct the optical depth by assuming that each grid cell has a Gaussian velocity distribution with a dispersion ($\sigma_{\mathrm{1D}}/2$), which is obtained from the line-of-sight velocity dispersion (σ_{los}) computed using the closest 27 neighbouring cells. We have tested the validity of the correction by using a high resolution in the NUT series (12 pc resolution; Devriendt et al. in preparation), and found that this procedure yields an accurate approximation of the maximum absorption strength and full width at half-maximum (FWHM) of the absorption profile that one would derive by using a much higher number of resolution elements. Finally, stars are assumed to dominate the UV emission, and we use the Maraston (2005) spectral energy distributions to derive the continuum flux around $\lambda \sim 1334$ Å, which depends on their mass, age and metallicity. The emission from each star particle in the galaxy is then used to estimate an observed flux, as attenuated by intervening gas present along the line of sight. Note that only the flux emitted by the central $10\,\mathrm{kpc}^2$ of a galaxy is used to compute the absorption line so as to mimic the observational resolution of FWHM $\simeq 0.40$ arcsec for galaxies at $z \sim 2$ (Steidel et al. 2010).

Fig. 2 shows the H I column density map, projected metallicity distribution and the corresponding absorption profile for a galaxy residing in a $M_{200} \sim 10^{12}\,\mathrm{M}_{\odot}$ halo at $z \sim 3.8$. A dense filament is clearly seen not only in the H column density map, but also in the metallicity map, with metallicity ($\sim 10^{-4}$ to $10^{-3}\,\mathrm{Z}_{\odot}$). The filamentary gas is receding from the observer; hence if detectable it should produce a redshifted absorption line. However, it turns out that the absorption signal is dominated by the ISM of the galaxy. When the absorption due to the ISM is arbitrarily removed by neglecting the

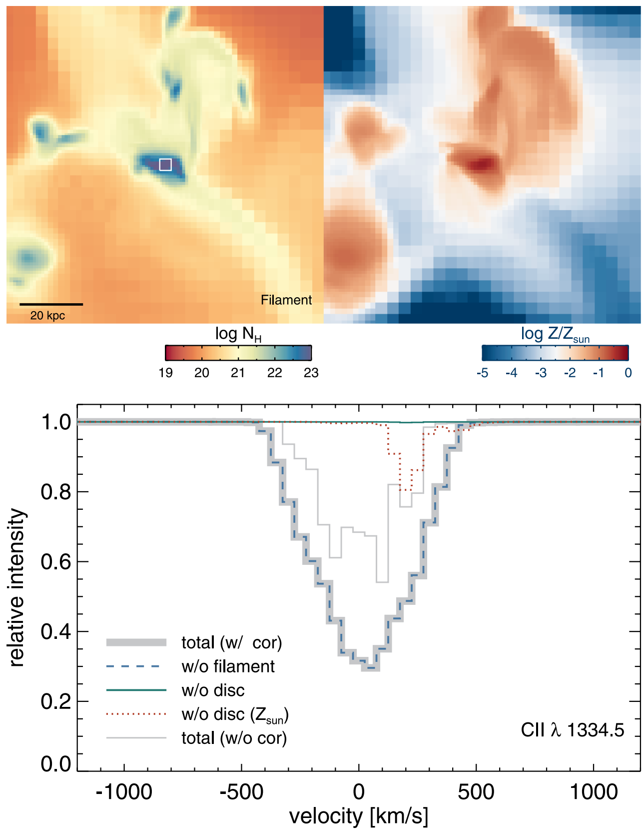

Figure 2. An example of the contribution from filamentary gas to the C II λ1334 absorption. Upper panels show the hydrogen column density and mass-weighted metallicity distributions for a $10^{12}\,\mathrm{M}_{\odot}$ halo at $z \sim 3.8$. A cold filament is indicated on the left-hand panel, which is receding from the observer and therefore should produce a redshifted absorption line. A white square denotes the central $\sim 10\,\mathrm{kpc}^2$ region over which the absorption spectrum is obtained. Bottom panel shows an absorption profile of this galaxy (thick grey solid line). We also compute the absorption without the central disc by neglecting the opacity of central cells ($r \leq 0.1 r_{200}$) (green solid line) and absorption without the outer gas ($r > 0.1 r_{200}$) (blue dashed line). Also included is the absorption produced when the outer gas ($r > 0.1\, r_{200}$) is assumed to have solar metallicity in the absence of the central disc (red dotted line). It can be seen that the contribution from the filament to the low-ionization metal line is negligible compared to that of the ISM of the galaxy in every case. An uncorrected spectrum is included to show the effect of the correction applied to the velocity distribution of gas (thin solid grey line).

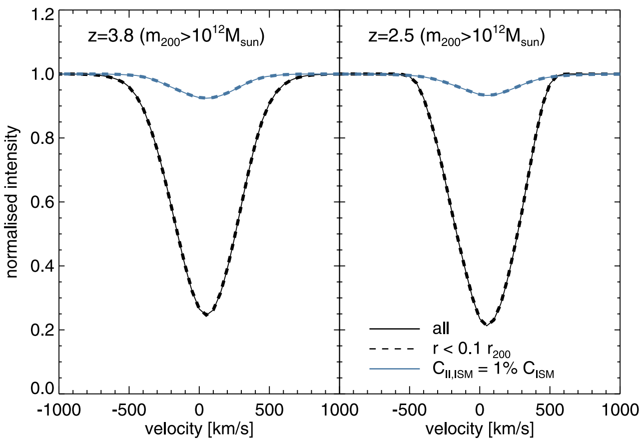

Figure 3. Stacked absorption profiles of massive galaxies ($M_{200} \geq 10^{12}\,\mathrm{M}_{\odot}$) at $z = 3.8$ (left) and $z = 2.5$ (right). We take six projections ($+x$, $-x$, $+y$, $-y$, $+z$, $-z$) for 132 galaxies at $z = 3.8$ and 386 galaxies at $z = 1.5$. The stacked spectra are obtained by taking the mean of the normalized intensity. We also show the absorption spectra expected when only a fraction (1 per cent) of the ISM carbon is assumed to produce the absorption (blue lines, see the text). The contribution from the outer regions (i.e. filament if any) is negligible in the absorption profile.

opacity from the gas inside the central gas disc ($r < 0.1\,r_{200}$), the absorption feature vanishes (green line). Even when the gas outside $r > 0.1\,r_{200}$ is assumed to have solar metallicity, the absorption strength is still much smaller (red dotted line) than the absorption produced by the galaxy's ISM (grey and blue dashed lines). This strongly suggests that the primary reason why it is so difficult to detect the cold filament is that the density of the filamentary gas is much lower than that of the galaxy's own ISM. As a result, and since the two absorption lines are not well enough separated in velocity space, the filament absorption signal is completely swamped by the high level of ISM absorption in the red wing of the line.

In order to see if we can bring out the filamentary signal by stacking absorption profiles, we analyse the absorption spectra of 132 and 386 massive galaxies ($M_{200} \geq 10^{12}\,\mathrm{M}_{\odot}$) at $z = 3.8$ and $z = 2.5$, respectively, along six projections ($+x$, $-x$, $+y$, $-y$, $+z$, $-z$) and find that the optical depth for the C II λ1334 transition by the filaments is fundamentally small regardless of redshift. Fig. 3 shows that the stacked (mean) absorption strength is unaffected by the presence of filaments. To check whether the signal from filaments could potentially become noticeable if the ISM was less metal-enriched, we also examined the case where only a tiny fraction (1 per cent) of the carbon in the ISM is eligible for the C II transition (blue lines in Fig. 3), but the difference between absorption profiles resulting from all the gas along the line of sight versus the case where we exclude the gas in the central region ($r < 0.1\,r_{200}$) is still minute. Therefore, we conclude that the presence of cold filaments is very difficult to confirm with low-ionization metal absorption lines.

The optical depth of filaments may be underestimated due to the finite resolution of the Horizon-MareNostrum simulation. For example, the density of the filamentary structure at $z = 7$ in the Horizon-MareNostrum simulation ($0.005 \lesssim n_{\mathrm{H}} \lesssim 0.1$) is more than an order of magnitude lower than that of the Nut simulation ($0.1 \lesssim n_{\mathrm{H}} \lesssim 1$) where the filaments are fully resolved (Powell et al. in preparation). However, this increase does not suffice to produce a strong absorption signal. Moreover, we find that the increasing resolution affects the ISM density more considerably (it becomes more than four orders of magnitude higher in the Nut than in the Horizon-MareNostrum simulation). As a consequence the ISM causes a stronger absorption signal, which more than compensates the increased contribution from the cold filament.

It should also be noted that finite resolution affects the metallicity of the filamentary gas, so that in the real Universe its metallicity may be higher than the values ($\sim 10^{-4}$ to $10^{-3}\,\mathrm{Z}_{\odot}$) we report for the Horizon-MareNostrum simulation. Indeed, our simulation cannot resolve all the small galaxies that might pollute the pristine filamentary gas. Besides, it is well known that the energy from supernovae will artificially be dissipated when simulations are run with an insufficient level of resolution. Indeed, in such a case, supernovae only explode in dense grid cells, resulting in substantial radiative losses and negligible momentum transfer to the surrounding gas. Under these circumstances, metals cannot disperse properly. For comparison, the ultra-high-resolution Nut simulation indicates that the metallicity of the filamentary gas around a $\sim 10^{9}\,\mathrm{M}_{\odot}$ galaxy can reach values up to $10^{-2}\,\mathrm{Z}_{\odot}$ already at $z \simeq 7$. Yet, such an increase in metallicity would still be inconsequential for the absorption spectra. Furthermore, we believe that the metallicity in the filaments is not likely to rise appreciably beyond these values, because most of the supernova ejecta escape in a direction perpendicular to that of the elongated filament, which makes it difficult to efficiently enrich the filamentary gas with metals (Geen, Slyz & Devriendt in preparation). However, for the sake of completeness, in Fig. 2 we present the case of a halo for which the gas outside $r > 0.1\,r_{200}$ is arbitrarily assumed to have solar metallicity. We find that the absorption strength of the filament (red dotted line) is still much smaller than the absorption produced by the galaxy's ISM.

4 CONCLUSIONS AND DISCUSSION

Cosmological simulations predict that high-z galaxies grow by acquiring gas from cold streams (Dekel et al. 2009), but no observational confirmation has been obtained yet. Based on a statistical sample from the Horizon-MareNostrum simulation, we argue that low-ionization metal absorption features, such as C II λ1334, arising from intervening cold filaments are extremely hard to distinguish from absorption by the ISM of high-z star-forming galaxies. This is primarily because the optical depth for the low-ionization transition from cold filamentary gas is minuscule, compared with that of the ISM of the host galaxy. Moreover, the filamentary absorption is not redshifted enough with respect to the ISM absorption, so that the residual ISM absorption in the red wing of the line is still prominent. This small optical depth of filaments mainly finds its source in the intrinsically low densities and metallicities of the cold gas when compared to those of the galaxy's ISM. Another factor is the geometry of the flow which lowers the probability of detecting filaments as their column density will rarely be maximized by being aligned with the line of sight.

As an alternative to using a single galaxy, one could probe circumgalactic regions by using a paired background galaxy. This method alleviates the importance of ISM absorption since when probing circumgalactic regions in this way, the absorption by the ISM of the foreground galaxy will occur at a different spatial position from that produced by filaments. Unfortunately, the rare occurrence of suitable foreground–background galaxy pairs makes it difficult to probe more than one line of sight per foreground galaxy. As a result, high-resolution individual spectra are hard to obtain and one has to resort to stacking the spectra of multiple galaxies (Steidel et al. 2010). Contrary to what might be expected, stacking will wash out the cold filament absorption signal since absorption by inflowing gas does not neatly separate from that caused by outflows as was the case when probing the circumgalactic region using single galaxies. Indeed, cold filament absorption against the background galaxy light will not only be redshifted, but also blueshifted as one expects that on average as many cold streams will be detected moving towards as away from the observer. Absorption by outflows will also suffer the same fate. This will make it all the more difficult to argue whether the observed absorption features are driven by infalling gas or by outflows from high-z star-forming galaxies. Moreover, the metal column density of cold filaments is minuscule, as already mentioned. The hydrogen column densities of the cold filaments are distributed around 10^{20} cm^{-2} at these redshifts, yielding corresponding carbon column densities around 10^{16} cm^{-2} if an average $Z = 0.001\,Z_{\odot}$ is used. Even if all carbon atoms are assumed to be eligible for the C II transition, the optical depth is only around 10^{-2} in the line. On the other hand, outflows are expected to be very metal rich, so that even though higher transitions like C IV are expected to dominate the absorption signal, the amount of C II absorption from these outflows might still swamp that produced by the cold filaments.

Finally, we have assessed possible numerical resolution issues on column density and metallicity of the filaments using the very high resolution numerical simulation NUT suite and found that our conclusions remain by and large unchanged.

Based on these considerations, we conclude that the presence of the cold filament is difficult to disprove/prove with low-ionization metal line absorption. Instead, the Lyman α emission route seems more promising to detect cold filaments, but the line profile is more sensitive to the kinematics of the intervening gas (Verhamme, Schaerer & Maselli 2006; Verhamme et al. 2008). Therefore this will require full blown radiative transfer calculations (e.g. Faucher-Giguère et al. 2011).

ACKNOWLEDGMENTS

The HORIZON-MARENOSTRUM simulation was run at the Barcelona Supercomputing Center and the NUT simulations at the CINES and the STFC HPC Facility DiRAC (Oxford node). CP acknowledges support from a Leverhulme visiting professorship at the Astrophysics department of the University of Oxford and TK from a Clarendon DPhil studentship. JD and AS'S research is supported by Adrian Beecroft, the Oxford Martin School and the STFC. We also acknowledge support from the Franco-Korean PHC STAR programme.

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