On the Detectability of Visible-wavelength Line Emission from the Local Circumgalactic and Intergalactic Medium

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Received 2018 November 2; revised 2019 April 9; accepted 2019 April 11; published 2019 May 16

Abstract

We describe a new approach to studying the intergalactic and circumgalactic medium in the local universe: direct detection through narrowband imaging of ultralow surface brightness visible-wavelength line emission. We use the hydrodynamical cosmological simulation EAGLE to investigate the expected brightness of this emission at low redshift ($z \lesssim 0.2$). H$\alpha$ emission in extended halos (analogous to the extended Ly$\alpha$ halos/blobs detected around galaxies at high redshifts) has a surface brightness of $\gtrsim 700$ photons cm$^{-2}$ s$^{-1}$ sr$^{-1}$ out to $\sim 100$ kpc. Mock observations show that the Dragonfly Telephoto Array, equipped with state-of-the-art narrowband filters, could directly image these structures in exposure times of $\sim 10$ hr. H$\alpha$ fluorescence emission from this gas can be used to place strong constraints on the local ultraviolet background and on gas flows around galaxies. Detecting H$\alpha$ emission from the diffuse intergalactic medium (the “cosmic web”) is beyond current capabilities but would be possible with a hypothetical 1000-lens Dragonfly array.

Key words: galaxies: evolution – galaxies: halos – intergalactic medium – large-scale structure of universe

1. Introduction

The intergalactic medium (IGM) and its close cousin, the circumgalactic medium (CGM), are arguably the most important baryonic components of the universe. The IGM is composed mainly of a diffuse plasma of primordial hydrogen and helium polluted by small quantities of metals produced by star formation. The near invisibility of the IGM (see below) masks its absolutely fundamental importance: the IGM contains the majority of baryons in the universe, and it is the ultimate source of fuel for the star formation occurring in galaxies (see, e.g., McQuinn 2016, for a review). In most models, this gaseous flow alongs the cosmic web of filamentary dark matter pervading the universe.

Galaxies form within dark matter halos at the intersections of the filaments. As the IGM gas falls into halos, it transitions into the CGM, the physics of which are a complex interplay between the large-scale dynamics of the infalling gas and feedback of reprocessed gas (and energy) back into the CGM from the galaxies themselves. The exact definition of the CGM is still debated, but it can be roughly described as being bounded by the disk or interstellar medium of the galaxy on the inside and the virial radius of a galaxy’s dark matter halo on the outside (see, e.g., Tumlinson et al. 2017, and references therein).

The CGM is central to building galaxies, but it is still poorly understood. The gas depletion timescale of galaxies is short (typically 1–2 Gyr), so accretion onto galaxies is necessary to sustain measured star formation rates (e.g., Bauermeister et al. 2010; van de Voort et al. 2011a). But beyond this, we know little about how galactic star formation is fueled by the IGM. We do not even know basic facts such as the typical amount of gas in the CGM, or even whether this gas is at the virial temperature of the halos. Because of this, we also do not know the processes by which this gas is accreted onto the central galaxy. Once the gas has made it into galaxies, we do not know how much gas is blown back out again by winds. This is also important because the porosity of the gas within the CGM determines how much ultraviolet radiation from galactic star formation leaks out into the IGM. Therefore, the effective range over which a typical galaxy influences the ionization state of the universe is not clear.

Why is so much still not understood about the IGM/CGM, particularly at low redshifts? In principle, some of the relevant physics of the CGM and IGM can be probed directly by H$\alpha$ imaging at 21 cm or molecular gas imaging with radio telescopes, since denser pockets of the CGM are in the form of “dark” clouds of neutral hydrogen and molecular gas. Thus far this approach has met with limited success (e.g., Oosterloo et al. 2007; Heald et al. 2011; Moss et al. 2017; Vargas et al. 2017; Emonts et al. 2018; Pingel et al. 2018). Single-dish radio telescopes have the required sensitivity to probe cold gas in halos in the nearby universe ($z < 0.1$), but they lack the needed resolution, while radio interferometers have the required resolution but lack the necessary dynamic range. Therefore, the majority of our observational constraints on the neutral components of the IGM come from studies of absorption systems. Since Ly$\alpha$ is a UV resonance line that must be cosmologically band-shifted in order to be accessible to ground-based telescopes, studies of Ly$\alpha$ absorption systems focus mainly on the characteristics of the IGM and CGM at redshifts $z > 2.5$, when Ly$\alpha$ becomes band-shifted into visible wavelengths. Ly$\alpha$ absorption systems at lower redshifts can only be investigated using space-based UV spectroscopy, and at present the only facility available for undertaking such work is the Cosmic Origins Spectrograph (COS) on the Hubble Space Telescope (HST; see, e.g., COS-Halos and other HST-COS surveys; Werk et al. 2013; Danforth et al. 2016; Richter et al. 2017). MgII absorption is similarly used as a tracer of neutral H column densities, observed in a redshift range that cannot be accessed by Ly$\alpha$ from the ground. Such investigations probe the IGM in dense pockets and in pencil beams where the CGM intersects with light from background sources.

For these reasons, the detailed investigation of the local CGM/IGM is a major goal of next-generation radio facilities, including the Square Kilometer Array.
Simulations of the CGM and IGM at intermediate redshifts (2 < z < 5) have reached the point that they are now quite successful at reproducing the observed column densities of H\textsc{i} probed by Ly\textalpha absorption systems (e.g., Altay et al. 2011; Rahmati et al. 2015). However, discrepancies begin to occur as these simulations are advanced in time to predict the properties of the IGM in the local universe: when one adds together the baryons contained in galaxies and those measured though Ly\textalpha absorption, the majority of baryons are not accounted for (McQuinn 2016). Unless high-redshift estimates of baryon content are incorrect, a large fraction of the low-redshift baryons have been missing in observations; a significant fraction of these “missing baryons” are thought to exist in the warm–hot intergalactic medium (WHIM) at $T \sim 10^5–10^7$ K, which is mostly invisible in Ly\textalpha absorption-line studies (see, e.g., Bertone et al. 2008, for a review). Studies of photoionized Ly\textalpha and highly ionized oxygen absorbers are starting to reveal gas in the WHIM, so far constraining the total baryonic fraction of gas in the WHIM to 24%–40% (e.g., Shull et al. 2012; Nicastro et al. 2018). In addition, there is a current debate over the total mass of gas in the cold ($T \sim 10^4$ K) CGM of L $\sim L_\odot$ galaxies, between $M_{\text{CGM}} \sim 3 \times 10^{10} M_\odot$ (Stocke et al. 2013; Keeney et al. 2017) and $M_{\text{CGM}} \sim 9 \times 10^{10} M_\odot$ (Werk et al. 2014; Prochaska et al. 2017), which increases the uncertainty of the total cosmic baryon mass.

An exciting alternative to absorption-line studies is direct imaging of emission from the IGM itself. At $\sim 10^5$ K, the warm–hot plasma is cooling radiatively by line emission, so the IGM is weakly luminous at UV and visible wavelengths. Fe\textsc{ii} and Mg\textsc{ii} emission from localized (<20 kpc radial distance) outflows of low-redshift star-forming galaxies has been detected (e.g., Rubin et al. 2011; Martin et al. 2013). Recently, more extended Ly\textalpha emission from the IGM or CGM at high redshifts has begun to be investigated by spatially resolved spectrometers such as the Cosmic Web Imagers (CWIs) on Keck and Palomar (Martin et al. 2010; Matuszewski et al. 2010) and the Multi Unit Spectroscopic Explorer (MUSE) on the Very Large Telescope (VLT; Bacon et al. 2010; Borissova et al. 2016; Wisotzki et al. 2016, 2018).

Ly\textalpha emission in low-redshift galaxies is not accessible from the ground, but an appreciable fraction of the energy emitted as ultraviolet photons also emerges in visible wavelengths (such as H\textalpha and [O\textsc{iii}] $\lambda 5007$). Furthermore, these lines may be easier to interpret than Ly\textalpha: diffuse Ly\textalpha emission in the outer halos of galaxies may be affected by the presence of resonantly scattered radiation suspected to originate from the central galactic H\textsc{ii} regions (see, e.g., Steidel et al. 2011), and low surface brightness measurements of a nonresonant line such as H\textalpha can help disentangle the properties of the CGM (e.g., Leibler et al. 2018).

Measurements obtained using other hydrogen emission lines, such as H\textbeta, may be cleaner probes of the CGM than Ly\textalpha, but is CGM emission from these lines practically detectable? Van de Voort & Schaye (2013) calculated H\textbeta line emission from the CGM in the optically thin limit for a specified UV background and predicted that an H\textalpha radial profile corresponding to the Ly\textalpha profile observed by Steidel et al. (2011) can be observed out to $0.2R_{\text{vir}}/0.6R_{\text{vir}}$ at a surface brightness limit$^7$ of $10^{-20}$ erg cm$^{-2}$ s$^{-1}$ arcsec$^{-2}$. Recent advances in low surface brightness imaging telescopes may have brought such observations into the realm of being practical. In this paper, we investigate whether it may be possible for ground-based telescopes to observe the cooling emission from the CGM/IGM in visible wavelengths. Our analysis is based on a subset of simulations from the Evolution and Assembly of GALaxies and their Environments (EAGLE) project (Crain et al. 2015; Schaye et al. 2015). We supplement the results from the simulation by calculating H\textalpha surface brightness estimates analytically from observations and theoretical considerations. We show that at low redshift H\textalpha emission from diffuse structures could be targeted through an upcoming narrowband imaging upgrade to the Dragonfly Telephoto Array (hereafter Dragonfly).$^8$

In Section 2, we briefly describe the EAGLE simulation and the numerical methods used to create emission maps. In Section 3, we describe the results of the EAGLE simulation. In Section 4, we apply the sensitivities of current instruments to the results from the simulation to determine the visibility of diffuse optical emission from the IGM and CGM. Throughout this paper, we assume a standard $\Lambda$CDM cosmology with Planck Collaboration et al. (2014) cosmological parameters: $\Omega_m = 0.307$, $\Omega_{\Lambda} = 0.693$, $\Omega_{b} = 0.04825$, $h = h_0/(100 \text{ km } s^{-1} \text{ Mpc}^{-1}) = 0.6777$. It should also be noted that throughout this paper all box sizes (as well as particle masses and gravitational softening lengths) are not quoted in units of $h^{-1}$.

2. Numerical Methods

2.1. The EAGLE Simulations

The EAGLE suite (Schaye et al. 2015) is a set of cosmological, hydrodynamical simulations of the standard $\Lambda$ cold dark matter universe where the values for cosmological parameters are taken from the 2014 Planck results (as stated in the previous section; Planck Collaboration et al. 2014). The simulations are produced with a modified version of the $N$-body Tree-PM smoothed particle hydrodynamics (SPH) code GADGET 3 (Springel 2005). The subgrid physics are based on the prescriptions applied in the OverWhelmingly Large Simulations (OWLS) project (Schaye et al. 2010), which has been used previously to investigate UV and X-ray line emission via cooling channels of diffuse IGM gas (e.g., Bertone et al. 2010a, 2010b, 2013; Bertone & Schaye 2012; van de Voort & Schaye 2013). The simulations include subgrid models for radiative cooling, star formation, stellar mass-loss and metal enrichment, energy feedback from star formation, gas accretion onto supermassive black holes, mergers of supermassive black holes, and active galactic nucleus feedback. Compared to OWLS, EAGLE has updated implementations of energy feedback from star formation (Dalla Vecchia & Schaye 2012), accretion of gas onto black holes (Rosas-Guevara et al. 2015; Schaye et al. 2015), and the star formation threshold (Schaye 2004).

In this study, we use the REFERENCE simulation at redshift $z = 0$ with a box size of 100 comoving Mpc, which contains $150^4$ particles with initial gas particle masses of $1.81 \times 10^6 M_\odot$ and dark matter particle masses of $9.70 \times 10^8 M_\odot$. The comoving gravitational softening is set to 2.66 kpc but is limited to 0.70 proper kpc from above. The box size and resolution of this

$^6$ The study of UV line emission from the IGM and CGM is one of the motivations for the proposed European–Chinese MESSIER satellite (Valls-Gabaud & MESSIER Collaboration 2017) and for the Canadian Space Agency’s proposed Cosmological Advanced Survey Telescope for Optical and UV Research (CASTOR) mission (Côtes et al. 2012)

$^7$ This is a conservative estimate since van de Voort & Schaye (2013) ignored self-shielding and H\textalpha powered by local star formation or local fluorescence, which could significantly boost the emission.

$^8$ http://www.dragonflytelescope.org/
The methods used to calculate the gas metal-line emission and create emission maps follow the prescriptions of Bertone et al. (2010a). We refer the interested reader to that work for more details, while giving a brief outline of the procedure here.

We used the line emissivity tables created by Bertone et al. (2010b), which were also used in Bertone et al. (2010a, 2013), Bertone & Schaye (2012), and van de Voort & Schaye (2013). The gas emissivity tables for each line were computed as a function of temperature, density, and redshift with CLOUDY version c07.02.02 (Ferland et al. 1998), under the assumptions of solar abundances, dust-free, optically thin gas, and photoionization equilibrium in the presence of the cosmic microwave background and the Haardt & Madau (2001) model for the evolving UV/X-ray background radiation from galaxies and quasars. Though more recent versions of CLOUDY exist, we use the same version of CLOUDY used by Wiersma et al. (2009) in order to ensure full self-consistency with the radiative cooling rates used in the EAGLE simulation. Following the prescription of Bertone et al. (2013), we adopt a solar abundance of $Z_0 = 0.0127$ corresponding to the default abundance set of CLOUDY version c07.02.02, which are a combination of abundances from Allende Prieto et al. (2001, 2002) and Holweger (2001) and may differ strongly from those estimated by Lodders (2003). In particular, the oxygen abundance adopted here is about 20% smaller than that of Lodders (2003). This should be kept in mind when comparing results of different studies, but we stress that the assumed solar abundances play no role when computing the emission from the EAGLE simulation, which is calculated using the absolute abundance predicted by the simulation. The tables include a total of about 2000 emission lines for 11 elements. The temperature is sampled in bins of $\Delta \log_{10} T = 0.05$ in the range $10^5 \text{ K} < T < 10^8.5 \text{ K}$ and the hydrogen number density in bins of $\Delta \log_{10} n_H = 0.2$ in the range $10^{-8} \text{ cm}^{-3} < n_H < 10 \text{ cm}^{-3}$.

The assumption of negligible self-shielding (i.e., optically thin gas) may break down in high-density (i.e., $n_H \gtrsim 10^{-2} \text{ cm}^{-3}$; Rahmati et al. 2013a), low-temperature (i.e., $T \lesssim 10^5 \text{ K}$) cases. At low densities, the hydrogen gas is predominantly photoionized (indicated by the smooth curves of the $n_H = 10^{-6} \text{ cm}^{-3}$ plot of Figure 1), but the gas is too diffuse for self-shielding to become important. At the dense gas, collisional excitation dominates at temperatures $T > 10^5 \text{ K}$ (indicated by the sharply peaked curves for hydrogen lines in the $n_H = 1 \text{ cm}^{-3}$ plot of Figure 1) and produces the brightest oxygen and hydrogen line emission, but a significant fraction of the hydrogen emissivity is also emitted from gas with $T < 10^5 \text{ K}$, which is photoionized (the tail of the hydrogen line curves at low temperature in the right panel of Figure 1). In addition, at transitional densities between these two regimes of ionization (e.g., middle panel of Figure 1) the emissivity from photoionization at $T < 10^5 \text{ K}$ for the hydrogen lines is comparable in strength to the emissivity from collisional ionization that peaks at $T > 10^5 \text{ K}$. Self-shielding may then be expected to be important for the hydrogen line emission, while the [O III] oxygen line emission, which peaks at $T > 10^5 \text{ K}$, may be less affected by self-shielding. At the densities and temperatures where self-shielding is expected to be important, though, the radiation from stellar sources, which is not included, is expected to become just as important as the ultraviolet background (UVB) and may counteract the effects of self-shielding (e.g., Rahmati et al. 2013b). We break down

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**Figure 1.** Emissivity of strong hydrogen lines H α and Ly α, as well as visible-wavelength oxygen lines, as a function of temperature for $z = 0$, solar abundance, and number densities $n_H = 10^{-6}$, and $10^{-8} \text{ cm}^{-3}$ in the right, middle, and left panels, respectively. Lines from the same ion are shown in the same color. An arrow is drawn in the left panel indicating the vertical shift that would occur for all the oxygen line emissivities when scaling from solar abundance to 0.01 solar abundance.
the contribution to the Hα emission from different sources, including star-forming and self-shielded gas, in Appendix A2.

The assumption of ionization equilibrium (for both the cooling rates and the emissivity tables) is justified for regions where they are predominantly photoionized, but in the WHIM and the outer regions of clusters, nonequilibrium processes may become important for metals (e.g., Gnat & Sternberg 2009; Bertone et al. 2010a; Oppenheimer & Schaye 2013, and references therein).

2.2. The Emission Maps

The procedure for computing the surface brightness emission maps follows that used in Bertone et al. (2010a), though we will include a brief description here for reference.

In OWLS, a constant threshold of $n_{\text{H}} > 10^{-4}$ cm$^{-3}$ was used to delineate when gas would become star-forming: above this density a cold phase is expected to form (Schaye 2004). EAGLE instead uses a metallicity-dependent density threshold, which takes into account the fact that the transition between the warm neutral phase and the cold molecular phase occurs at lower density and pressure if the metallicity is higher (Schaye 2004; Schaye et al. 2015). Since EAGLE does not model the cold gas phase (instead imposing a temperature floor according to a polytropic equation of state; Schaye & Dalla Vecchia 2008), we either set the emission from star-forming gas to zero or use an empirically motivated prescription to calculate Hα emission from the star-forming gas. The empirical prescription takes the rate of star formation in the gas and the measured conversion factor, $C_\alpha$, between star formation rate and intrinsic Hα luminosity (specifically, $\log M_\alpha = \log L_\alpha - \log C_\alpha$, where $(C_\alpha/\text{erg s}^{-1} M_{\odot}^{-1} \text{yr}) = 41.27$; Kennicutt & Evans 2012) to calculate the amount of Hα emission from the star-forming gas. In other words, for star-forming gas, we are assuming that the emission is dominated by recombination radiation from H II regions.

We assign star-forming emission based on this empirical calibration of the star-forming gas rather than modeling star particles as single stellar populations to estimate the Hα emission from star-forming regions, as the low number of young star particles in the simulation would cause poor sampling. Note that resonant scattering is neglected but is expected to be important for the distribution of Lyα emission (e.g., Faucher-Giguère et al. 2010; Bertone & Schaye 2012).

To estimate the surface brightness in emission lines from the simulation in order to predict the detectability of the diffuse emission, the properties of the particles in the simulation box are projected onto a spatial grid, and then slices of this projected box are taken in radial distance. Specifically, the luminosity, $L$, of the particle is $L_{\alpha,i} = \epsilon_{\alpha,i}(\rho, T_i, z) V_i [X_{\text{H}_\alpha}/X_{\text{H}_\alpha}] \text{ erg s}^{-1}$, where the element is designated by $y$, the particle identifier is $i$, $\epsilon(\rho, T_i, z)$ is emissivity interpolated from the CLOUDY tables at solar abundance, $V_i$ is the volume of the particle calculated from the particle mass and density, and $X$ is the mass fraction, using SPH-smoothed abundances. Explicitly, $X_{\text{H}_\alpha}$ is the mass fraction of element $y$ in particle $i$, and $X_{\text{H}_\alpha}$ is the solar mass fraction of element $y$. We note again that we omit star-forming gas when calculating the emission using the CLOUDY tables, so there is no double accounting for the emission from the star-forming regions. The flux from the particle is

$$F_i = \frac{L_i \lambda (1 + z)}{4\pi D_L^2 h_{\text{pc}}}$$

in units of photons cm$^{-2}$ s$^{-1}$, where $h_{\text{pc}}$ is Planck’s constant, $D_L$ is the luminosity distance of the emitter, $\lambda$ is the rest-frame wavelength of the emitted photons, and $c$ is the speed of light.

For our analysis, we use emission maps from the 100 Mpc box simulation, with a slice width of 20 comoving Mpc. The depth of the slice, 20 comoving Mpc, corresponds to a wavelength shift of $\approx 3$ nm or $\approx 1400$ km s$^{-1}$ at $\lambda = 656.3$ nm (of order the average velocity dispersion of galaxy clusters).

Emission maps for Lyα, Hα, and [O III] $\lambda 5007$ are shown in the top row of panels in Figure 2 encompassing a node of the cosmic web where a galaxy group has formed. These maps are created from the simulation at redshift $z = 0$ and are 4 × 4 comoving Mpc on a side. The physical resolution of the emission maps is 6.25 kpc pixel$^{-1}$ (for reference, this corresponds to an angular resolution of $\approx 10''$ for structures at a radial distance of 75 Mpc, while the total length, 4 comoving Mpc, corresponds to an angular scale of $\approx 1''$). Only non-star-forming particles are included in the emission maps of Figure 2. In Figure 2, we also show maps of the ratio of emission between Lyα and Hα (bottom middle panel) and between Lyα and [O III] $\lambda 5007$ (bottom right panel). The Lyα emission and Hα emission traces the diffuse gas in the simulation, whereas the oxygen line emission is concentrated in the denser gas pockets. Though Lyα emission and Hα emission are produced by similar mechanisms—predominantly photoionization that increases in strength as temperature decreases—the Lyα-to-Hα ratio is not constant owing to the presence of different sources of emission, which include collisional excitation, collisional ionization, and photoionization. At different temperatures and densities, different emission sources become significant, which produces various ratios of Lyα to Hα photons. In practice, the Lyα emission is brighter by up to a factor of $\approx 20$ in emission compared to the Hα emission, but for the majority of the diffuse emission the relative surface brightness of Lyα to Hα is $\approx 8$.

It is interesting to note that the oxygen line emission is relatively stronger than both the Lyα and the Hα emission—in dense pockets of gas, where the [O III] $\lambda 5007$ emission is brighter than the Lyα emission by up to an order of magnitude. This contrasts with emission from diffuse structures, where the Lyα emission dominates by many orders of magnitude. Though the [O III] lines have strongly peaked emission at the temperatures of the WHIM (as seen in Figure 1), it is predominantly collisionally ionized, and the strength of the emission also depends on the abundance of the ion and the density of the gas, which boosts the oxygen emission in dense pockets where the metallicity is higher rather than in the diffuse cosmic web.

It would be valuable to measure the oxygen emission to place constraints on the metallicity and exchange of material.

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10. Note that we neglect dust extinction, which is typically between 0 and 1 mag at Hα (Kennicutt & Evans 2012).

11. We note that these ratio maps are ratios of emission in photons: to convert to ratios of emission in energy, one can simply multiply by the ratio of the line wavelengths.
from the galaxies to the CGM and IGM. From this simple comparison, it appears that the oxygen emission will have similar detectability to the Hα that we find here (if not being more detectable). While the following analysis and discussion focus on Hα emission, our findings for the detectability of Hα emission from the CGM can be applied to [O III] emission as well. Finally, we reiterate that we ignored emission from the interstellar medium, i.e., the star-forming gas, which may dominate the brightest regions.

3. Instruments

We now turn to the practical aspects of the detectability of emission from the IGM and CGM, starting with a consideration of instruments. There are a number of ground-based instruments that have come online in the past few years that are designed to probe diffuse emission from the IGM at z > 1.5 and may also be applied to imaging the cosmic web through visible-wavelength emission. These include the Cosmic Web Imager (PCWI; Matuszewski et al. 2010) on the 200" Hale Telescope at Palomar, the MUSE (Bacon et al. 2010) on the VLT, and the Keck Cosmic Web Imager (KCWI; Morrissey et al. 2012, 2018). We note that the balloon-borne experiment FIREBall (Quiret et al. 2014) is designed to image Lyα emission from the cosmic web at redshift z ~ 0.7, but its wavelength range does not include visible-wavelength emission. Another note is that the KCWI wavelength range currently does not cover the Hα line (the blue channel covers 350–560 nm), but the planned red channel will open the full wavelength range to 350–1050 nm and allow Hα studies.

PCWI, KCWI, and MUSE have wavelength ranges in the visible spectrum and have reached extremely low surface brightness limits targeting low surface brightness emission from the CGM and IGM at high redshift.12 Here we focus on the detectability of Hα emission with Dragonfly, but the characteristics of these instruments are listed in Table 1, for reference.

Dragonfly is currently being upgraded to support narrow-band imaging work. In its present 48-lens configuration, the telescope is equivalent to a 0.99 m aperture, f/0.4 telescope, with a 2′6 × 1′9 field of view (FOV). Dragonfly’s large FOV and low resolution, combined with its low surface brightness capabilities, make it uniquely suited to imaging spatially very extended, extremely low surface brightness structures, such as ultra diffuse galaxies (Abraham & van Dokkum 2014). Dragonfly has imaged down to surface brightnesses around ~32 mag arcsec−2 in g band. To determine the sensitivity of Dragonfly as a narrowband imager, we will use the following specifications to describe the telescope system: the transmittance of the lenses (τf = 0.85) and filters (τf = 0.95), a narrowband filter width of 3 nm, the quantum efficiency of the

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12 While it is difficult to compare the surface brightness limits reached by instruments owing to differences in observing conditions and modes, we note that in observations targeting low surface brightness extended emission (over a 10−15 arcmin scale) PCWI has reached a detection limit of LSB ≈ 1.3 × 10−19 erg s−1 cm−2 arcsec−2 (Martin et al. 2014a) and MUSE reaches the same depth for an aperture of 1′ (Wisotzki et al. 2018).
Table 1
Characteristics of KCWI\(^a\) (Morrissey et al. 2012, 2018), PCWI (Matuszewski et al. 2010), MUSE (Bacon et al. 2010), and FIREBall (Quiret et al. 2014), as well as the Redshift Range for which the \(\text{Ly}\alpha\) and \(\text{H}\alpha\) Transitions Fall into the Wavelength Range of the Instrument

| Instrument  | Wavelength Range (Å) | FOV (arcsec) | Pixel Size (arcsec) | \(z\) Range \(\text{Ly}\alpha\) (1216 Å) | \(z\) Range \(\text{H}\alpha\) (6563 Å) | Spectral Resolution |
|-------------|----------------------|--------------|---------------------|-------------------------------|-----------------------------|-------------------|
| PCWI        | 3800–9500            | 60 × 40      | 2.5 × 1             | 2.1–6.8                       | 0–0.45                      | 5000              |
| KCWI        | 3500–10500           | 20 × (8–33)  | 0.5 × (0.35–1.4)    | 1.9–7.6                       | 0–0.60                      | 900–1800\(^b\)    |
| MUSE        | 4650–9300            | 60 × 60      | 0.2                 | 2.8–6.6                       | 0–0.42                      | 1750–3750\(^c\)   |
| FIREBall-2  | 2000–2080            | 1200 × 1200  | 4                   | 0.64–0.71                     | ...                         | 2150              |

Notes.
\(\^a\) Note that the full proposed KCWI wavelength coverage is listed here. KCWI currently has only a blue channel with a wavelength range of 3500–5600 Å, which does not cover the \(\text{H}\alpha\) transition.
\(\^b\) Depends on chosen grating and IFU slicer configuration.
\(\^c\) Smoothly varies from the blue end to the red end of the wavelength range.

detectors (QE = 0.70), along with their dark current (\(D = 0.04\) electrons s\(^{-1}\) pixel\(^{-1}\)) and read noise (\(R = 2\) electrons pixel\(^{-1}\)).

An estimate of the sky background within the filter bandwidth is found by integrating the flux of the Gemini model spectrum of the sky background within the bandwidth of the Dragonfly narrowband filters. In this case we make a realistic assumption for the Dragonfly Telescope observing conditions, where on average 50% of nights are darker than the adopted sky brightness. This value is obtained from a Gemini model sky spectrum,\(^{13}\) which is scaled to match the sky brightness at the 50th percentile (at around \(\lambda = 656.3\) nm the integrated sky background within the filter width is \(\approx 2.2 \times 10^6\) photons s\(^{-1}\) nm\(^{-1}\) cm\(^{-2}\) sr\(^{-1}\)).\(^{14}\)

With these values, the signal-to-noise ratio (S/N) can be calculated as

\[
S/N = \frac{I}{\sqrt{(I + Bn + Dn)\tau + R^2n}},
\]

where \(I\) is the count rate, \(B\) is the sky background per pixel, and \(n\) is the number of pixels. The exposure time, \(\tau\), is usually given in seconds. Both \(I\) and \(B\) depend on the total transmittance of the camera, \(\tau = \tau_l \times \tau_f\).

Equation (2) indicates that with a 3 nm narrowband filter on Dragonfly, a surface brightness of 1000 photons s\(^{-1}\) cm\(^{-2}\) sr\(^{-1}\) can be reached with an S/N \(\approx 5\) in \(\approx 60\) hr when targeting 100\(^\circ\) features (see Figure 6). As we will now show, the structures in the local universe are very large. By exploiting its large FOV, Dragonfly is likely to be able to probe the IGM and CGM in the local universe down to depths similar to those reached by KCWI and MUSE on much larger telescopes at high redshifts.

The spatially resolved spectrometers mentioned above were designed to image the high-redshift cosmic web with their relatively small FOVs matched to the angular scale of the cosmic web at redshift \(z > 1.5\). The FOVs for each instrument are maximally \(60 \times 40\)\(^\circ\) for CWI, \(20 \times 34\)\(^\circ\) for KCWI, and \(60 \times 60\)\(^\circ\) for MUSE. In Figure 3, we compare the MUSE FOV to the Dragonfly FOV by projecting the FOVs onto the EAGLE simulation. The dashed lines outline the size of the Dragonfly/MUSE FOV when targeting structures in the local universe at distances of \(\approx 50, 200, 500,\) and \(1000\) Mpc (corresponding to redshifts of \(z \approx 0.01, 0.05, 0.12,\) and 0.24). Figure 3 demonstrates that it may be possible for the spatially resolved spectrometers to observe \(\text{H}\alpha\) emission from the CGM of local galaxies, while the filamentary structures of the IGM in the local universe extend to far larger scales than their FOVs. An additional consideration is the effect of scattering in the telescope optics: in typical telescope optical design, the scattering of light from central star-forming regions causes the surface brightness background level to rise and may wipe out the signal from the extremely faint diffuse gas. Dragonfly’s all-refractive design minimizes scattered light, so, in principle, it is particularly well suited to probing the local CGM and IGM. We explore this idea further in the next section.

4. Detectability of the CGM and IGM in the Local Universe

4.1. CGM

In this section, we move from the general considerations of the previous section to explore predictions for the visibility of the local CGM and IGM in detail. For the following analysis, we will specifically consider \(\text{H}\alpha\) emission because it closely traces the gas in the diffuse CGM and IGM and is accessible from the ground. We assume Dragonfly with 3 nm bandwidth filters mounted at the entrance apertures of each lens in the array (the configuration is described in detail in D. Lokhorst et al. 2019, in preparation, an instrumental companion to the present paper). We include emission from both star-forming and non-star-forming particles for the following analysis (see Section 2.2 for details) and use the EAGLE Galaxy Catalogue (McAlpine et al. 2016) to select galaxies by stellar masses, half-stellar-mass radii, half-gas-mass radii, and location.

In Figure 4, the Dragonfly FOV when imaging structures 50 Mpc away is shown centered on a sample region from the EAGLE simulation. The slice thickness of the simulation is the
Figure 3. Hα surface brightness mapped from the full EAGLE 100 Mpc simulation box at redshift $z = 0$ (with a 20 Mpc width) projected to the size of the Dragonfly FOV, $2'6 \times 1'9$ (left panel), and the size of the MUSE FOV, $60'' \times 60''$ (right panel), at redshift $z \sim 0.24$ (corresponding to a radial distance of $\sim 1000$ Mpc). The dashed green (blue) lines in the left (right) panel correspond to the size of the Dragonfly (MUSE) FOV at redshifts of $\sim 0.01$, $0.05$, and $0.12$ or radial distances of $50$, $200$, and $500$ Mpc. An example filament of the IGM is indicated by the white dashed box.

Figure 4. The central panel depicts a cutout from the EAGLE simulation in Hα emission that is the size of the Dragonfly FOV at a distance of 50 Mpc, with a slice thickness of 20 comoving Mpc. The physical resolution in each map is $3.125$ kpc pixel$^{-1}$, which corresponds to $\approx 13''$ angular resolution. Zoom-ins on galaxies from the cutout that have stellar masses greater than $10^9 M_\odot$ are shown on either side (each zoom-in is 200 comoving kpc on a side). The stellar masses and half-stellar-mass radii ($r_{\text{half, star}}$) of the selected galaxies are labeled on each zoom-in. The blue circles overplotted on the zoom-ins correspond to $r_{\text{half, star}}$ of each galaxy. The red circles overplotted on the zoom-ins correspond to $5 \times r_{\text{half, star}}$ for the selected galaxy—generally the limit for detections of stars in galaxies (surface brightnesses of less than 32 mag arcsec$^{-2}$; Bland-Hawthorn et al. 2005; Zhang et al. 2018). An inset image of NGC 300 from the DSS is provided for reference, with the outermost radius corresponding to the red circle. Note how coherent structures are traced by diffuse line emission that extends far beyond the stellar components of the galaxies.
differentiate between the individual galaxies. The individual galaxies are labeled with numbers corresponding to the same objects in Figure 4. Of the six galaxies, those brighter than $32$ mag are plotted in green, and the galaxies with stellar mass between $10^{10}$ and $10^{11} M_\odot$ are plotted in blue, with varying line styles to differentiate between the individual galaxies.

same as that used in Section 2.2 (i.e., 20 comoving Mpc), where the entire slice is assumed to be at the same redshift. The field is centered on a typical filament of the cosmic web, with boxes drawn around all galaxies with stellar masses greater than $10^9 M_\odot$ within the FOV. Zoom-ins for each galaxy are also shown where each cutout has side lengths of 200 kpc.

From the zoom-ins, it is clear that the galaxies in the EAGLE simulation have a wide variety of gas properties, in both their mass and their distribution. On each of the zoom-ins, the blue circles are drawn at the half-stellar-mass radius ($r_{h,\text{star}}$) of each galaxy, and red circles indicate $5 \times r_{h,\text{star}}$ for the galaxy. The limit of $5 \times r_{h,\text{star}}$ corresponds to the radial limit for detections of stars in galaxies when imaging down to surface brightnesses fainter than 32 mag$^{-2}$ (Bland-Hawthorn et al. 2005; Zhang et al. 2018). For reference, an inset of NGC 300 is shown where its outermost radius corresponds to $5 \times r_{h,\text{light}}$. Note how coherent structures are traced by diffuse line emission that extends far beyond the stellar components of the galaxies.

Azimuthally averaged radial Hα surface brightness profiles around galaxies in the EAGLE simulation are shown in Figure 5. The median radial profiles for galaxies within a specified mass range are shown in Figure 5, superimposed on the backdrop of the individual profiles for each individual galaxy in light gray. In the left (middle; right) panel, all galaxies with stellar masses of $10^9 M_\odot$–$10^{10} M_\odot$ ($10^{10} M_\odot$–$10^{11} M_\odot$; $10^{11} M_\odot$ and up) are shown and the median profile is plotted in green (blue; orange), with a lighter-colored shaded area indicating the 25th to 75th percentiles. The median virial radius for galaxies within each mass bin is indicated on the top $x$-axis (using the $R_{200}$ definition of the virial radius to normalize). The individual radial Hα profiles for the six galaxies with zoom-ins in Figure 4 are also plotted in Figure 5: the three galaxies with stellar mass between $10^9$ and $10^{10} M_\odot$ are plotted in the left panel, and the three galaxies with stellar mass between $10^{10}$ and $10^{11} M_\odot$ are plotted in the middle panel. The profiles in each mass bin are close to power law in shape. Note that galaxy (iii) is fainter than the more massive galaxies overall, but for some radii it has comparable Hα brightness. This is interesting because it implies that similarly bright extended halos can be found around a large mass range of galaxies, despite the marked difference when considering the statistical trends. In addition, this demonstrates that although the average surface brightness profiles are useful for getting an idea of the brightness profile, individual profiles can be much brighter (or fainter) than the averages, making them much easier (or harder) to detect. In the following sections we investigate the visibility of gas in the CGM, considering extended halos in Section 4.1.1, gas streaming into and around galaxies in Section 4.1.2, and photoluminescence from the cosmic UVB in Section 4.1.3.

4.1.1. Predicted Visibility of Extended Halos

Figures 4 and 5 illustrate a predicted “glow” from the gas filling the halos of galaxies, which has not yet been observed locally. At higher redshifts this phenomenon was first detected in stacked images by Hayashino et al. (2004) and later on was shown to be ubiquitous around very actively star-forming galaxies by Steidel et al. (2011), who used deep narrowband imaging around the Lyα line to look for extended structure around very actively star-forming Lyman break galaxies at redshift $z \approx 2.5$. By stacking 92 individual galaxies and azimuthally averaging, Steidel et al. (2011) found that there was an excess diffuse Lyα component that extended out to $\approx 80$ kpc (reaching surface brightness $SB_{\text{Ly}\alpha} \sim 10^{-19}$ erg s$^{-1}$ arcsec$^{-2}$ cm$^{-2}$), compared to the continuum emission, which stopped at $\approx 10$ kpc. Similar stacking analyses of thousands of star-forming galaxies in various environments at redshifts $z \sim 3–6$ have followed that corroborate the existence of extended Lyα halos with luminosities and
sizes that vary depending on the environment (with various filtering and averaging methods these studies reach surface brightnesses $SB_{\alpha} \sim 10^{-19} - 10^{-21}$ erg s$^{-1}$ arcsec$^{-2}$ cm$^{-2}$ and radii $\approx 30-80$ kpc; e.g., Matsuda et al. 2012; Momose et al. 2014, 2016; Wisotzki et al. 2018). With MUSE, Wisotzki et al. (2016, 2018) detected halos of extended Ly$\alpha$ emission around individual galaxies at redshifts of $\sim 3-6$, which extend out to $\approx 50-70$ kpc and reach surface brightnesses $SB_{\alpha} \sim 10^{-19} - 10^{-20}$ erg s$^{-1}$ arcsec$^{-2}$ cm$^{-2}$ through azimuthal averaging (note that the first hints of Ly$\alpha$ halos around individual galaxies were detected earlier by Rauch et al. 2008). In addition, extended Ly$\alpha$ nebulae around quasars at redshift $z \sim 2-4$ have been observed to have sizes as large as $\sim 300$ kpc at similar surface brightnesses (e.g., Borisova et al. 2016; Arrigoni Battaia et al. 2018; Cai et al. 2018).

We can use these existing high-redshift results to check the reasonableness of the numerical simulations we have just shown. To compare our predictions with the higher-redshift observations, we estimate the strength of H$\alpha$ emission in the extended halo by converting the Ly$\alpha$ surface brightness measurements at higher redshift to H$\alpha$ estimates through a series of physical relations. For this estimate, we use the Steidel et al. (2011) results, which are fairly representative of the various high-redshift Ly$\alpha$ emission measurements and would correspond to highly star-forming galaxies at the low redshifts. We first make a simple assumption that the emission is cooling radiation emitted by cold accretion flows in the form of cold, dense gas. Here we ignore that some fraction of the Ly$\alpha$ emission is predicted to be produced through resonant scattering of Ly$\alpha$ from inner galactic regions into the halo and instead assume that all Ly$\alpha$ emission is produced in situ, which may cause us to overestimate the extended H$\alpha$ emission. In this case, the Ly$\alpha$ emission may be produced primarily from collisional excitation of the gas, rather than recombination. Specifically, we (i) assume that the location where the Ly$\alpha$ and H$\alpha$ emission originates is the same, (ii) assume the ratio of emissivity for H$\alpha$ to Ly$\alpha$ for collisional excitation, (iii) correct for cosmological effects on the luminosity, and (iv) ignore resonant scattering of Ly$\alpha$. Note that the emissivity ratio for H$\alpha$ to Ly$\alpha$ for collisionally excited gas is $\approx 1/100$ (Dijkstra 2014). Using this method, we estimate that at $\approx 80$ kpc, the limit out to which Steidel et al. (2011) observe, the surface brightness in H$\alpha$ is $\approx 1.6 \times 10^{-19}$ erg s$^{-1}$ arcsec$^{-2}$ cm$^{-2}$ or $\approx 2250$ photons cm$^{-2}$ sr$^{-1}$ s$^{-1}$. This is roughly consistent with the azimuthally averaged radial profiles of the high-mass galaxies ($m_{\text{gal}} > 10^{11} M_{\odot}$) from the EAGLE simulation, shown in Figure 5.

If the Ly$\alpha$ emission in extended halos is mainly originating from photoionized gas, we also need to account for changes in the star formation rate and lowering of the UV-ionizing background (in the case that the Ly$\alpha$ emission originates from UV background-ionized gas). A simple method of scaling from basic physical processes will not suffice in this case, so instead we turn to the EAGLE simulation.

The azimuthally averaged radial profiles of the CGM of galaxies in EAGLE (see Figure 5) allow us to estimate the surface brightness of H$\alpha$ emission from the extended halos. For each mass bin, the median H$\alpha$ surface brightness is, respectively, $SB_{\alpha,\text{CGM,inner}} \approx 160, 4800$, and $3000$ photons cm$^{-2}$ sr$^{-1}$ s$^{-1}$ at the inner edge of the CGM. Interestingly, the inner edge of the CGM defined by $\sim 5 \times r_{\text{h,star}}$ is brighter for the middle mass bin than for the largest mass bin. While this may be due to small number statistics (there are 19 galaxies with $m_{\text{gal}} > 10^{11} M_{\odot}$ contained in the $100$ cMpc $\times 100$ cMpc $\times 20$ cMpc EAGLE simulation box considered here), this could indicate a difference in buildup mechanism (i.e., gas falls more directly into the smaller mass galaxies and builds up to create a steeper profile, whereas pressure support of virialized gas in the halos of higher-mass galaxies, as well as the heating of infalling gas, prevents gas from falling directly into the galaxy causing a shallower density profile of gas and translating into a shallower slope for the H$\alpha$ surface brightness). In any case, this demonstrates that it is not necessary to focus on extremely massive galaxies to detect the CGM in H$\alpha$ emission, as galaxies in the middle mass bin are just as bright.

The median surface brightness of the profiles shown in Figure 5 drops off quickly, falling to $\sim 1$ photon cm$^{-2}$ sr$^{-1}$ s$^{-1}$ by $\approx 0.2 R/R_{200}$, $0.4 R/R_{200}$, and $0.3 R/R_{200}$ for the lowest, middle, and highest mass bins, respectively. As can be seen from the individual galaxy profiles, there are exceptions to the median profile, and indeed, galaxy (iii) in the lowest mass bin is brighter by two orders of magnitude than the median brightness at $\approx 0.2 R/R_{200}$. Using the largest mass bin at a radius of $100$ kpc as the reference point for estimating the H$\alpha$ surface brightness in the extended halo yields a surface brightness from EAGLE of $SB_{\alpha,\text{H} \alpha} \approx 700$ photons cm$^{-2}$ sr$^{-1}$ s$^{-1}$. 

Figure 6. S/N for the Dragonfly Telescope narrowband imaging at $\lambda = 656.3$ nm as a function of integration time for specific surface brightnesses (indicated by the color map). The surface brightnesses are calculated for $50^\prime$ ($100^\prime$, $150^\prime$) square features in the left (middle; right) panel. In addition to the color map, the contours also show surface brightness to guide the eye.
Figure 7. Sample galaxy from the EAGLE simulation (galaxy (iii) from Figure 4) shown here in the leftmost panel. Superimposed on the image is an inset of an actual galaxy (NGC 300 from the DSS) to demonstrate the spatial scale of the gaseous structure. The inset image of NGC 300 has been spatially scaled to match the scale length of the simulation (assuming that the half-stellar-mass radius and half-light radius of a galaxy are roughly equal; e.g., Szomoru et al. 2011). The red circle drawn on the image corresponds to \(5 \times \text{half-stellar-mass radius (}\rho_{\text{halo}}\text{)}\) of the EAGLE galaxy. This radius corresponds to the typical scale we would mask to exclude gas inside the galaxy and leaves only gas surrounding the galaxy in the CGM. Mock Dragonfly observations of the sample galaxy are shown in the second through fourth panels. The second (third; fourth) panel corresponds to an observation with an exposure time of 10 hr (100; 1000 hr) with Dragonfly.

Figure 6; azimuthal averaging at radii of 100 kpc corresponds out to a radius of 100 kpc is \(\approx 1500\) photons \(\text{cm}^{-2} \text{sr}^{-1} \text{s}^{-1}\); therefore, at an angular distance of 100", the scattered light is \(\approx 10\) photons \(\text{cm}^{-2} \text{sr}^{-1} \text{s}^{-1}\). The extended wings of the Dragonfly point-spread function have not been fully characterized, but the point-spread function can be reasonably well approximated by a double Moffat profile with an aureole component (as described in, e.g., Racine 1996). We convolve the simulation with this point-spread function (taking the entire projected Dragonfly FOV and then cutting out the region of interest) to approximate the scattering of light we would observe.

In Figure 7, we show a sample galaxy from the EAGLE simulation in the left panel. This galaxy has a gaseous halo of H\(\alpha\)-emitting gas that appears to be spiraling inward, but it could also be a gas disk that extends far out into the CGM. Note that the spectral resolution of Dragonfly narrowband filters is not high enough to differentiate between inward or outward motions, so emission from all dense streams and clumps of gas (whether infalling or outflowing) will be captured. The second through fourth panels of this figure show mock observations of the simulated data in the leftmost panel, with different exposure times. In the second (third; fourth) panel, the exposure time used to create the mock observation is 10 hr (100; 1000 hr) with Dragonfly. The pixel scale is 3.125 kpc or \(\approx 13\)" at the projected distance (for reference,
Dragonfly’s angular resolution is $2''8$. In the projected Dragonfly FOV, the star-forming regions have surface brightnesses up to $\sim10^{6.5}$ photons cm$^{-2}$ sr$^{-1}$ s$^{-1}$, resulting in scattered light of $\sim10^{1.5}$ photons cm$^{-2}$ sr$^{-1}$ s$^{-1}$ at the inner edge of the CGM, which is about an order of magnitude fainter than the brightness of the CGM gas emission. In each panel, we also include an inset of an actual galaxy, NGC 300, which has been scaled spatially to match the scale length of the simulation, assuming that the half-stellar-mass radius and half-light radius are roughly equal.$^{15}$ One can see that the spiraling gas structure extends much farther than the disk of the galaxy: the red circle corresponds to what is considered to be the half-light radius ($r_{h,\mathrm{star}}$) of the EAGLE galaxy, as for the galaxy cutouts from Figure 4. Based on Figure 7, we conclude that just 10 hr of integration with Dragonfly will allow us to directly observe dense regions of gas outside the outermost limit of the edge of the galaxy (defined by the maximum extent of stellar light) without azimuthally averaging. In very long (100–1000 hr) integrations, more of the emission is captured, but the emission is so faint that even heroic integrations do not fully reveal the gas. The outskirts of the gas in the CGM of this mock observation may, however, be observable with azimuthal averaging (as was described in the previous section).

4.1.3. Predicted Visibility of Photoluminescence from the UVB

In the EAGLE simulations, gas in the CGM and IGM fragments into clouds or clumps, which may be related to so-called “dark clouds” or “dark galaxies.” Recent H I 21 cm surveys have uncovered many “dark galaxy” candidates, which are H I clouds with no detected optical counterparts of significant association (for a recent summary, see Taylor et al. 2016), and similar candidates have been found through Ly$\alpha$ emission around high-redshift quasars with MUSE (Marino et al. 2018). Fluorescent line emission induced by the cosmic UVB from optically thick (to ionizing radiation) H I “skins” of such intergalactic clouds has never been observed but has long been predicted, though Marino et al. (2018) observed Ly$\alpha$ fluorescent emission from dark galaxies that is most likely quasar induced and Fumagalli et al. (2017) observed H$\alpha$ fluorescent emission from the disk of a galaxy that is most likely UVB induced. Observations of fluorescent emission from true intergalactic dark galaxies/clouds would place very strong constraints on the (local and/or global) UV-ionizing background, which is currently ill constrained. Many of these dark H I clouds are $>100$ kpc from their nearest galaxy and, as such, would make good candidates for detecting H$\alpha$ fluorescence. It is important to know the UV background intensity, since many predictions for CGM absorption and emission depend on it.

Studies of UVB-induced H$\alpha$ emission from dark H I clouds in the local universe are limited, with one example being that of Donahue et al. (1995), who undertook narrowband H$\alpha$ imaging on three intergalactic H I clouds in an attempt to measure the UV-ionizing background, probing down to surface brightnesses of $\sim10^{-18}$ erg s$^{-1}$ cm$^{-2}$ sr$^{-1}$. They found nondetections for their two targets that were isolated from any galaxies and thus more likely to emit H$\alpha$ only through UV background ionization. To estimate the required exposure time to observe UVB-induced H$\alpha$ emission, we use estimates of the ionizing UV background and radiative transfer physics to describe the excitation of H clouds and the intensity of the line emission that would result. Assuming case B recombination at $T \sim 10^4$ K, about 45% of the incident ionizing photons result in H$\alpha$ photons (Osterbrock & Ferland 2006), and the flux of H$\alpha$ can be estimated to be

$$\Phi_{H\alpha} = \frac{J_0 f_{H\alpha}}{h f f_{s}}$$

(3)

where $J_0$ is the UV-ionizing background, $h$ is Planck’s constant, $f_{H\alpha}$ is a geometrical correction factor, $f_{H\alpha} \approx 0.45$, and $f_s$ is an adjustment for the spectral shape of the ionizing background. Assuming that the cloud is optically thin to H$\alpha$ photons and illuminated by the UVB on all sides, the H$\alpha$ flux depends on the ratio of the cloud’s surface area to its projected area, which is accounted for by the geometrical factor, $f_s$ (Stocke et al. 1991). Since $f_s$ and $f_{H\alpha}$ are unknown, we consider a best-case scenario (i.e., spherical cloud, high ionization background; $J_0 \approx 10^{-22}$ erg s$^{-1}$ cm$^{-2}$ sr$^{-1}$ Hz$^{-1}$ and $f_s \cdot f_{H\alpha} \approx 1$; e.g., Donahue et al. 1995; Faucher-Giguère et al. 2009), a pessimistic scenario (i.e., spherical cloud, low ionization background; $J_0 \approx 10^{-23}$ erg s$^{-1}$ cm$^{-2}$ sr$^{-1}$ Hz$^{-1}$ and $f_s \cdot f_{H\alpha} \approx 1$; e.g., Donahue et al. 1995; Faucher-Giguère et al. 2009), and a worst-case scenario (i.e., irregularly shaped clouds, low ionization background; $J_0 \approx 10^{-23}$ erg s$^{-1}$ cm$^{-2}$ sr$^{-1}$ Hz$^{-1}$ and $f_s \cdot f_{H\alpha} \approx 3.26$; e.g., Donahue et al. 1995; Haardt & Madau 2012), and a worst-case scenario (i.e., irregularly shaped clouds, low ionization background; $J_0 \approx 10^{-23}$ erg s$^{-1}$ cm$^{-2}$ sr$^{-1}$ Hz$^{-1}$ and $f_s \cdot f_{H\alpha} \approx 3.26$; e.g., Donahue et al. 1995; Faucher-Giguère et al. 2012). With an S/N calculated by binning over the number of pixels corresponding to an angular size of $2' \times 2'$ (following methods of Donahue et al. 1995), Dragonfly can reach S/N $\approx 5$ in $\approx 15$ minutes and $\approx 2.5$ hr for the best-case and nominal case scenarios, respectively. The integration time increases to tens of hours for the pessimistic case, and up to 1000 hr for the worst case. This estimate does not take into account limb brightening, which boosts the radiation at the edges of the clouds, and may allow one to be slightly more optimistic than the numbers just presented.

Photoluminescence by the UVB can also be targeted by measuring H$\alpha$ emission from the edges of disks of late-type galaxies. Fumagalli et al. (2017) used MUSE to detect H$\alpha$ emission in the outskirts of the galactic disk of UGC 7321 down to surface brightnesses of $\sim1 \times 10^{-19}$ erg cm$^{-2}$ arcsec$^{-2}$ or $\sim1400$ photons cm$^{-2}$ sr$^{-1}$ and provided constraints on the UVB at $z = 0$. Binning to 100$''$ scale features (which is double with the large FOV of Dragonfly), we predict that this surface brightness can be detected at $5\sigma$ in $\approx 15$ hr of integration (see the middle panel of Figure 6) with Dragonfly, allowing similar constraints on the UVB in the local universe to be made.

4.2. Predicted Visibility of the Warm–Hot IGM

While imaging of extended emission from cooling CGM gas in galaxy halos would be extraordinarily interesting, there is no doubt that the “holy grail” would be the detection of gas emission from outside halos and in the IGM itself. While monumentally difficult (as we will show), the most spectacular observation would be to directly image the IGM in

$^{15}$ For reference, the mass and size of the EAGLE galaxy and NGC 300 are not identical: the EAGLE galaxy has a stellar mass of $\sim5 \times 10^9 M_\odot$ and $r_{h,\mathrm{star}} \sim 4.8$ kpc, whereas NGC 300 has a stellar mass of $\sim2.1 \times 10^9 M_\odot$ (assuming an M/L ratio of 1) and $r_{h,\mathrm{light}} \sim 3.0$ kpc (McConnachie 2012).
the cosmic web. The simplest analytical arguments suggest that this observation is so difficult as to be effectively hopeless, though we will show that numerical predictions are not quite as pessimistic.

At low redshift, the filamentary IGM is predicted to be mainly collisionally ionized (e.g., Bertone et al. 2008), so emission occurs via radiative cooling, as discussed in Bertone et al. (2013). To determine the amount of energy emitted in lines detectable by Dragonfly, we need an estimate of the cosmic web density and mass. As a first estimate, we imagine that the IGM is simply gas at the mean density in the universe with an average temperature of \( T \sim 10^5 \) K (targeting collisionally ionized gas). The mean density of the universe corresponds to a hydrogen number density of \( n_{\text{H}} \sim 4 \times 10^{-7} \, \text{cm}^{-3} \) at \( z \sim 0 \). We take a ballpark estimate of the width of IGM filaments from the simulations of \( L \sim 0.5 \, \text{Mpc} \sim 1.5 \times 10^{24} \, \text{cm} \). This corresponds to a hydrogen column density \( N_{\text{H}} \sim 10^{18} \, \text{cm}^{-2} \). The emission measure (EM) of the IGM filaments can be approximated as \( \text{EM} = \int n_e^2 \, ds \approx n_e^2 L \), where the integral is evaluated over the length scale of the filament. The effective recombination rate coefficient for \( \text{H} \alpha \) emission can be calculated with Equation (14.8) of Draine (2011), which yields \( \alpha_{\text{eff}} \approx 1.13 \times 10^{-14} \, \text{cm}^3 \, \text{s}^{-1} \) at \( T \sim 10^5 \) K. This rate coefficient is calculated assuming Case B recombination, which may not be strictly true for the IGM but suffices for a crude estimate. The emission rate of \( \text{H} \alpha \) photons is \( F_{\text{H} \alpha} = \alpha_{\text{eff}} \text{EM} \approx 0.006 \, \text{photons cm}^{-2} \, \text{s}^{-1} \). The surface brightness, \( F/\Omega \), is then calculated as \( S_{\text{BH} \alpha} = F/(4\pi) \approx 0.0005 \, \text{photons cm}^{-2} \, \text{s}^{-1} \, \text{sr}^{-1} \). Clearly, this is extremely faint.

To better approximate filaments in the IGM, we can reasonably assume an average density for the IGM of \( n_{\text{H}} \times 10 \) (Bertone et al. 2008; McQuinn 2016). Following the calculation outlined above, we arrive at a surface brightness \( S_{\text{BH} \alpha} \approx 0.5 \, \text{photons cm}^{-2} \, \text{s}^{-1} \, \text{sr}^{-1} \), which is still very, very faint—about \( 1000 \times \) fainter than the extended halos just considered, meaning they would take \( \sim 1 \) million times longer to image!

A somewhat more optimistic picture emerges if we treat the IGM as a multiphase medium with clumps even denser than \( n_{\text{H}} \times 10 \). EAGLE allows us to explore this (arguably more realistic) picture of the IGM and its emission. In the top left panel of Figure 8 a zoom-in on an example filament of the IGM from EAGLE is displayed. In the EAGLE simulation, the \( \text{H} \alpha \) surface brightness of the gas in the IGM ranges from \( \sim 100 \) photons \( \text{cm}^{-2} \, \text{s}^{-1} \, \text{sr}^{-1} \) (in dense regions near galaxies) to \( 0.1 \) photons \( \text{cm}^{-2} \, \text{s}^{-1} \, \text{sr}^{-1} \) (in isolated, diffuse filaments). This is consistent with that estimated from the order-of-magnitude approximation for the isolated regions where the gas is extremely diffuse.

In Figure 8, mock Dragonfly observations are plotted for an example filament of the IGM from EAGLE (indicated by the white dashed box in Figure 3). The mock observations are created by adding noise and convolving with the Dragonfly point-spread function as described in Section 4.1.2. The top left panel of Figure 8 shows the raw EAGLE data for the example filament. Before we create the mock observations, we make a mask for the filament to mask out emission from the galaxies. In the top right panel, the mask is shown: each galaxy in the filament is masked out to a radius of \( 5 \times r_{\text{H} \alpha} \), where the median \( \text{H} \alpha \) brightness, \( \text{EM} \), is binned to a resolution of \( \sim 100'' \) (250", 500"). In the left column, we bin the data without using the mask. We compare this with the right column, where the mask shown in the top right panel was applied before binning the data; thus, in the right column the emission peaks in the mock observations are nominally from gas outside of galaxies. We confirm this supposition in Appendix A2. Though the filamentary structure itself remains elusive in this mock observation, it is clear that there are bright sources of \( \text{H} \alpha \) emission outside of galaxies.

It should be noted that in the EAGLE simulation portions of the filamentary IGM emission reach surface brightnesses of \( \sim 1 \) photon \( \text{cm}^{-2} \, \text{s}^{-1} \, \text{sr}^{-1} \), which is of order the brightness of scattered light emission from star-forming regions (as approximated by the characterization of the Dragonfly point-spread function; see discussion in Section 4.1.2). To attain the goal of imaging IGM filaments, down to the surface brightness of \( 1 \) photon \( \text{cm}^{-2} \, \text{s}^{-1} \, \text{sr}^{-1} \) that the EAGLE simulations suggest, extreme binning and upgrades to Dragonfly (e.g., more lenses, new cameras) are necessary. As is shown in Figure 6, even with azimuthal averaging (or extreme binning), a surface brightness of 100 photons \( \text{cm}^{-2} \, \text{s}^{-1} \, \text{sr}^{-1} \) is barely reachable in 1000 hr of exposure time with Dragonfly as it stands.

5. Discussion and Conclusions

The hydrodynamical simulations presented here show that direct imaging (at visible wavelengths) of cooling emission from the local CGM is now a practical possibility. Such observations are made practical by technical advances in spatially resolved spectroscopy (Bacon et al. 2010; Matuszewski et al. 2010; Morrissey et al. 2012, 2018; Quiret et al. 2014) and low surface brightness imaging (Abraham & van Dokkum 2014; Lokhorst et al. 2019, in preparation). With appropriate control of systematics (see below), it will be possible to extend the most recent generation of local \( \text{H} \alpha \) galaxy surveys (e.g., Meurer et al. 2006; Kennicutt et al. 2008; Gavazzi et al. 2012; Boselli et al. 2015; Van Sistine et al. 2016), as well as deeper studies of star formation in local galaxies (e.g., Lee et al. 2016), out to radii where line emission becomes dominated by gas cooling rather than by photoionization. Such observations would provide a powerful extension of existing techniques for the exploration of the disk–halo interface of galaxies (and of the CGM generally), which have relied mainly on absorption-line spectroscopy using pencil-beam surveys. Since direct imaging at visible wavelengths probes gaseous material at temperatures and densities typical of baryons in the local universe, these observations would usefully augment investigations focusing on gas in other phases probed by radio (cold gas) and X-ray (hot gas) wavelengths.

The easiest way to characterize warm–hot gaseous emission in the local CGM will be to target the extended halos of galaxies, since the S/N level of these structures can be boosted by azimuthal averaging. In only 1 hr of integration time, a mosaic telescope similar to the Dragonfly Telephoto Array with a set of 3 nm bandpass narrowband filters16 could readily observe \( \text{H} \alpha \) emission at the inner edge of the CGM (for which we have adopted the definition of \( 5 \times r_{\text{H} \alpha} \)), where the median \( \text{H} \alpha \)

16 An experimental setup with 3 nm filters is under construction and preliminary results will be presented in a companion paper. This imager is based on a six-lens telephoto array with full aperture filters. Central wavelengths are chosen to avoid galactic \( \text{H} \alpha \) emission, and a differential background subtraction technique (based on tilting the filters to shift their bandpasses) is used to minimize sky contamination. The interested reader is referred to Lokhorst et al. (2019, in preparation) for details.
emission is approximately 3000–5000 photons s$^{-1}$ cm$^{-2}$ sr$^{-1}$ for galaxies at redshift $z \sim 0$ with stellar masses $\geq 10^{10} M_\odot$ (see Section 4.1.1). This radius corresponds to the outermost distance at which starlight has been detected in the disks of galaxies. Pushing to more ambitious integration times would allow one to probe out to radii well beyond those at which stars are seen in local disk galaxies. For example, EAGLE predicts that a narrowband imaging telescope with similar characteristics to Dragonfly would be able to map radial profiles down to surface brightnesses of $\sim 700$ photons s$^{-1}$ cm$^{-2}$ sr$^{-1}$ with exposure times of around 40 hr. This would allow the detection of H$\alpha$ emission out to radii of around 100 kpc (for a galaxy with stellar mass $\geq 10^{11} M_\odot$).

These predictions are based on EAGLE, but one can obtain similar numbers using empirical arguments. For example, we have shown that the Ly$\alpha$ halo surface brightness profile measured by Steidel et al. (2011) at high redshift can be used to predict the corresponding H$\alpha$ surface brightness of the halos of local galaxies. Assuming that the emission is produced through cooling radiation, H$\alpha$ emission would be $\sim 4$ times stronger than that predicted by the EAGLE simulation. This may simply be a reflection of the fact that the observed emission is the product of both cooling radiation and photoionization by star-forming regions or even by the extragalactic UV background.\footnote{Measurement of Ly$\alpha$ at low surface brightness is complicated by the fact that Ly$\alpha$ is a resonantly scattering line, so it is possible for star-forming regions to light up emission in the outskirts of the galaxy, decoupling the line strength from the gas density (e.g., Faucher-Giguère et al. 2010). H$\alpha$ is not a resonant scatterer, so it will trace the gas density more closely.}

In any case, the main point is that a local star-forming galaxy with properties similar to those of the (admittedly fairly extreme) high-redshift objects studied by Steidel et al. (2011) would almost certainly show an H$\alpha$ halo that would be readily detectable by a narrowband imager optimized for the detection of low surface brightness structures.

Moving beyond the investigation of axisymmetric structures makes the prospects for observing emission from the local CGM/IGM more nuanced. It would be extremely challenging to detect gaseous emission from the largest-scale filamentary structure in the local universe (i.e., from material very distant from halos and confined only by the gravity of the cosmic web). The surface brightness of H$\alpha$ emission from this filamentary emission is extremely low, at only a few photons s$^{-1}$ cm$^{-2}$ sr$^{-1}$. Even when using very narrow bandpass filters (such as the 3 nm bandwidth filters described in Lokhorst et al. in prep.) and binning to extremely low spatial resolution ($\sim 100''$ FWHM beams), a Dragonfly-like telescope would require integration times of tens of thousands of hours to trace out directly the structure of the cosmic web over something like ten degrees of sky. This seems hopeless, but at present the world’s largest mosaic telescope (Dragonfly) has the effective aperture of only a 1 m telescope. The effective aperture of small telescope arrays can be scaled up relatively easily, and because they build up aperture by averaging over many beams, control over systematics grows in lockstep with the size of the array. There is some hope that in the future the direct detection of even the “deep” cosmic web will fall within the reach of a large mosaic telescope array. In the meantime, statistical methods may be used to augment direct imaging approaches for investigating the cosmic web, e.g., via cross-correlation of extended H$\alpha$ or [O III] emission with the positions of galaxies, etc. etc.
as was done by Croft et al. (2016) with Ly$\alpha$ emitters and quasars in the Sloan Digital Sky Survey at intermediate redshift.

Focusing on volumes of space closer to galaxies brings us to a very interesting (and observationally tractable) regime, where the CGM of the galaxies is dominated by nonaxisymmetric inflowing gas (e.g., Martin et al. 2014a, 2014b). The present paper suggests that detecting the diffuse gas in streams is now a realistic prospect. The requisite observations would take a Dragonfly-like telescope significant (but realistically achievable) amounts of time—EAGLE suggests that unbinned integration times range from tens of hours with optimistic assumptions to thousands of hours with pessimistic assumptions. Observations of the more diffuse components of the CGM could perhaps be undertaken with extreme binning, but a better strategy might be to focus on the detection of dense pockets in these streams. Clumps of gas in streams may be related to dark H I clouds that have been observed near galaxies and have no stellar counterparts. As suggested by Donahue et al. (1995), if these clouds are far enough away from galaxies, they will be solely illuminated by the UV-ionizing background, and observations of line emission from them would allow an estimate to be made of the local UV-ionizing background. The UV-ionizing background at redshift $z \sim 0$ is currently only constrained to within two orders of magnitude (see, e.g., Fumagalli et al. 2017, for a recent summary), and placing better constraints on this important parameter would appear to be both relatively straightforward and of great interest.

The central message of the present paper is this: direct imaging at visible wavelengths of gas inflow and feedback at the disk–halo interface of local galaxies is now a tractable observational problem. Parallel progress mapping Ly$\alpha$ emission from gas in the CGM/IGM is being made at high redshifts using spatially resolved spectrometers such as MUSE and KCWI (Martin et al. 2014b, 2016;Wisotzki et al. 2016), with particular success targeting quasar-illuminated gas (Martin et al. 2014a; Borisova et al. 2016). Additionally, in even more local environments than those considered here, progress has been made in the detections of baryons in the halo of the Milky Way through stacking of Sloan Digital Sky Survey spectra (Zhang & Zaritsky 2017). The significance of this progress is that we will soon be able to undertake observations that characterize directly the relationship between galaxy growth (both in gas and in stars) and feedback (inflows and outflows). In doing so, we will also be imaging the hidden dominant component of the universe’s baryons, which, together with dark matter, acts behind the scenes to control the formation of galaxies.

We thank C. Matzner for useful conversations about the analytical calculations in this paper and the anonymous referee whose helpful comments lead to improvements in the manuscript. We are thankful for contributions from the Dunlap Institute (funded through an endowment established by the David Dunlap family and the University of Toronto).

Appendix

A1. Convergence Test

In this section, we present a test to verify the convergence of the predictions from the simulation with different numerical resolutions. We compare emission maps from four simulations:REF376, REF752, RECAL752, and REF1504.REF376 and REF1504 are “intermediate-resolution” simulations, with initial baryonic particle masses of $1.81 \times 10^8 M_\odot$ and gravitational softening lengths of 0.70 proper kpc, whileREF752 and RECAL752 are “high-resolution” simulations, with initial baryonic particle masses of $2.26 \times 10^5 M_\odot$ and gravitational softening lengths of 0.35 proper kpc.REF1504 is the simulation used in the main analysis of this paper and has a box size of 100 comoving Mpc.

**Figure 9.** Comparison of H$\alpha$ azimuthally averaged surface brightness profiles from four EAGLE runs: REF376, REF752, RECAL752, and REF1504.REF752 and RECAL752 are higher-resolution runs with box size of 25 cMpc.REF376 and REF1504 are lower-resolution simulations with box sizes of 25 and 100 cMpc, respectively (REF1504 is the simulation used in the main analysis of this paper). In the left panel, the median H$\alpha$ surface brightness profiles for galaxies with stellar mass $M_*>10^9 M_\odot$ are shown for each simulation, with same-colored shading filling the area between the 25th and 75th percentiles. In the right panel, the H$\alpha$ surface brightness profiles for galaxies in three mass bins ($10^8 M_\odot$–$10^9 M_\odot$, $10^9 M_\odot$–$10^{10} M_\odot$, and $10^{10} M_\odot$ and up) are shown for each simulation. For clarity, the REF1504 simulation is left out of the right panel. The profiles are consistent with one another within the scatter, though the higher-resolution runs trend to higher surface brightnesses.
whereas the other three simulations have box sizes of 25 comoving Mpc.

Figure 9 shows the H$\alpha$ azimuthally averaged surface brightness profiles for each simulation. Although the differences between the median profiles of the different simulations are consistent with each other within the galaxy-to-galaxy scatter, there are significant variations particularly at large radii, where the higher-resolution simulations predict higher surface brightnesses for each mass bin. We hypothesize that the higher-resolution runs introduce more density peaks into the simulation, which boosts the H$\alpha$ emission; hence, the results based on the 100 cMpc box used throughout are conservative with regard to the detectability of the CGM.

A2. Contribution of Sources of Emission

In this section, we calculate the emission maps from the EAGLE simulation from separate sources of emission and compare the results. In the first case, we calculate the emission from all gas particles, including star-forming particles, using the prescription outlined in Section 2, where the non-star-forming gas particles are assumed to be optically thin to the metagalactic ionizing radiation (this is the prescription used in the analysis of the main part of this paper). In the second case, we include emission from all non-star-forming gas particles (leaving out star-forming gas). In the third case, we apply the prescription outlined in Rahmati et al. (2013a) to estimate the effects of self-shielding in the simulation. We use Equations (A1) and (A8) from the analysis of Rahmati et al. (2013a) to calculate the neutral fraction in each non-star-forming gas particle and omit this fraction from the emission calculation. This is a conservative estimate of the effects of self-shielding, since we completely remove the optically thick fraction of gas from the particle (neglecting that a fraction of this gas in the outer shell will also see ionizing radiation and emit H$\alpha$ emission). To correctly account for the fluorescent H$\alpha$ emission of optically thick clouds, it is necessary to perform a full radiative transfer calculation, which is beyond the scope of this work. These cases thus reflect the range in which we expect the H$\alpha$ emission to lie in reality. It is important to note that for the second and third prescriptions applied here, we ignore the effect of ionizing radiation from local sources, such as young stars and quasars, which are expected to become important for the gas particles at densities where self-shielding from the UVB comes into play as demonstrated by the first case, i.e., emission from local sources may boost the emission even more where the emission drops as a result of self-shielding (Rahmati et al. 2013b).

In Figure 10, we show the emission maps for each case side by side. By eye, it is difficult to see any difference in these maps, except in the central regions of galaxies. In Figure 11, we compare the H$\alpha$ azimuthally averaged surface brightness profiles for each case. The first case differs from the second and third cases by more than two orders of magnitude at radii inside the galaxy, whereas at the inner edge of the CGM they
converge to similar values (i.e., star-forming and self-shielded gas is concentrated within the galaxies). For comparison, the H$_\alpha$ surface brightness for optically thick clouds arising from recombination following photoionization by the UV background can be computed following Equation (5) of Gould & Weinberg (1996), where $\phi(\nu)$ is given by the Haardt & Madau (2001) spectrum and $\eta_{\text{thick}}$ is the number of H$_\alpha$ photons per incident ionizing photon for case B recombination (assuming that the gas temperature of 10$^4$ K yields $\eta_{\text{thick}} = 0.45$). This results in an H$_\alpha$ surface brightness of $\approx 1 \times 10^3$ photons s$^{-1}$ cm$^{-2}$ sr$^{-1}$. This estimate agrees well with the maximum surface brightness of the third case considered here (the blue line in Figure 11); while the third case includes only optically thin gas, at its maximum surface brightness the emission is coming from clouds that are very close to being optically thick, so this agreement is reassuring. We conclude that although the effect of local sources of ionizing radiation, and to a lesser extent self-shielding, is large within galaxies, the predictions of the different prescriptions converge in the CGM.

In Figure 12, we test the effects of not including star-forming gas particles in the mock observations of the IGM, to isolate emission from the CGM and IGM gas. We reproduce Figure 8 in the left column of panels and compare this to an identical set of panels in the right column, except that these panels were made without including emission from star-forming particles, i.e., not including galactic gas. We compare the mock observations side by side, with star-forming gas included (omitted) in the left (right) column of panels. One can see that even when sources of emission within the galaxies are omitted (in the right panels), the emission left over from the CGM and IGM is still significant.

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Figure 12. Left column of panels redisplayed from Figure 8. Comparison of the emission from the CGM and IGM including the star-forming gas (in the left column) to emission omitting star-forming gas (right column). It is clear that even when omitting star-forming gas to isolate extragalactic gas emission from galactic emission, there are still significant sources of emission.

18 Note that this calculation differs from the simulation in that it assumes case B rather than case A recombination, assumes a constant gas temperature of 10$^4$ K, and ignores emission processes other than recombination. The calculation is consistent with the simulation in that dust is ignored.
