CONTINUUM EMISSION BY COOLING CLOUDS

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ABSTRACT

The collapse of baryons into the center of a host dark matter halo is accompanied by radiation that may be detectable as compact (<10 kpc) UV-continuum and Lyα emission with Lyα luminosities as high as \( \sim 10^{42} - 10^{43} \) erg s\(^{-1}\) in halos of mass \( M = 10^{11} - 10^{12} M_\odot \). We show that the observed equivalent width (EW) of the Lyα line emitted by these cooling clouds is \( \text{EW} \lesssim 400 \) Å (restframe). These luminosities and EWs are comparable to those detected in narrowband surveys for redshifted Lyα emission. The rest-frame ultraviolet of Lyα emitting cooling clouds radiation may be dominated by two-photon transitions from 2s to 1s. The resulting spectrum can distinguish cooling clouds from a broad class of young star forming galaxies.

Subject headings: cosmology: theory–galaxies: high redshift–galaxies: formation–radiation mechanisms: general

1. INTRODUCTION

Gas collapse into the center of a host dark matter halo requires the release of gravitational binding energy in the form of cooling radiation. The efficiency of gas cooling therefore plays an important role in the formation of stars and galaxies. For example, it has been shown that trapping of cooling radiation can affect the fragmentation of a collapsing gas cloud (Spaans & Silk 2006). Understanding cooling radiation is therefore essential in our understanding of galaxy formation. A large fraction of cooling radiation may emerge as Lyα emission (Haiman et al. 2000; Fardal et al. 2001), possibly accompanied by emission from helium (Yang et al. 2006). Galaxies may therefore be visible as extended Lyα sources before star formation occurs. This realization coincides with the discovery of two large Lyα ‘blobs’ (LABs) by Steidel et al. (2000). Naturally, LABs have been associated with cooling radiation.

Since the discovery of LABs by Steidel et al. (2000) several tens of new LABs have been discovered (Matsuda et al. 2006; Dev et al. 2005; Saito et al. 2006; Ouchi et al. 2008). Various groups have investigated what powers Lyα emission in LABs (e.g. Matsuda et al. 2006; Saito et al. 2007). Recent studies suggest that the majority is likely powered by (obscured) stars and/or AGN (e.g. Basu-Zych & Scharf 2004; Matsuda et al. 2007), or by a superwind (e.g. Taniguchi & Shioya 2000; Mori et al. 2004). However, in some LABs it is possible to rule out all these mechanisms, as each is expected to produce characteristic metal lines at flux levels that are not detected. This has led to the conclusion that cooling radiation may have been detected (Nilsson et al. 2006; Saito et al. 2007; Smith & Jarvis 2007).

Cooling radiation may also manifest itself as compact Lyα emission (rather than spatially extended) with luminosities comparable to those observed in high-redshift Lyα emitting galaxies. Haiman et al. (2004) pointed out that \(~ 30\%\) of their total computed cooling luminosity may originate from the central \(~ 10\%\) in radius. Furthermore, Fardal et al. (2001) and Yang et al. (2006) found that spatially extended cooling gas clouds in 3-D simulations contain dense compact clumps (< 10 kpc, \( n_{H_{\text{max}}} \approx 50 \) cm\(^{-3}\) which dominate the total Lyα cooling emission.

\(^1\) Extended Lyα emission is quite common around radio galaxies, and is thought to be powered by some sort of jet-IGM interaction (e.g. Chambers et al. 1999; Villar-Martín 2007). However, the LABs discovered by Steidel et al. (2000) have no associated radio-galaxies.

\(^2\) The term ‘Lyα cooling radiation’ that is used throughout this paper refers to both real (i.e. collisionally excited) cooling radiation, as well as Lyα radiation that is emitted as a by-product of recombination cooling (even though Lyα radiation that is produced in radiative cascades following recombination is technically not cooling radiation, since it does not transport any heat from the gas). In both cases, the Lyα radiation is emitted in a ‘proto-galactic’ gas cloud that is still collapsing to form stars. Furthermore, for neutral fractions as low as \( x_n = 10^{-4}\), the ‘real’ Lyα cooling rate due to collisional excitation, \( \dot{M}_{\text{Ly}\alpha} \) is equal to the Lyα emission rate due to recombination (for \( T_{\text{rec}} = 3 \times 10^4 \) K, see Appendix B). Hence, even recombing H II regions can emit a significant amount of Lyα cooling radiation.

\(^3\) We compute the continuum emission of cooling clouds redward of Lyα, and show that this is dominated by two-photon transitions from 2s to 1s. The spectrum of this continuum has a peculiar shape which may distinguish cooling clouds from young star forming galaxies.

The outline of this paper is as follows. In § 2 we illustrate that cooling radiation may be detectable as compact Lyα emission. This is followed by a calculation of the spectrum of cooling radiation at wavelengths redward of Lyα in § 3. Finally, in § 4 we discuss the results of this paper, and present our main conclusions.
2. COMPACT L\(\alpha\) COOLING RADIATION

We use a modified version of a one-dimensional (spherically symmetric) hydrodynamical code originally written by Thoul & Weinberg (1995). For a detailed description of the code the reader is referred to Thoul & Weinberg (1995). The modifications are described in Dijkstra et al. (2004). The goal of this section is to emphasize the possibility that the L\(\alpha\) luminosity of compact cooling clouds is comparable to that of star forming galaxies.

We focus on one particular simulation in which a dark matter halo of mass \(M_{\text{halo}}/M_\odot = 10^{11.5}\) collapses at \(z_c = 4.5\). Such an object is expected to have a L\(\alpha\) luminosity of \(L_\alpha \sim\) a few \(10^{42}\) erg s\(^{-1}\) (Haiman et al. 2000), which is within the range of luminosities that is probed by existing L\(\alpha\) surveys (e.g. Ouchi et al. 2008a). At redshift \(z = 4.5\) the Universe was \(\sim 1.4\) Gyr old. We take snapshots of the simulation at intervals of 75 M\(\text{yr}\) and read out quantities such as gas density, velocity, cooling rates etc.

The top panel of Figure 1 shows the radial evolution of mass shells initially enclosing \(M_{\text{tot}}/M_\odot = 10.5, 11\) and 11.5 (see labels). The lower horizontal axis shows the age of the Universe in Gyr, while the upper shows redshift. Each shell initially expands with the Hubble flow and is subsequently decelerated by the enclosed mass until it collapses. The lower three panels show the total Ly\(\alpha\) luminosity outside a sphere of radius \(R\) as a function of \(R\), i.e. \(L_{\text{Ly}\alpha}(R) = 4\pi \int_{r_\text{min}}^{R} r^2 \, dr \, j_\alpha(r)\). The reason for plotting this quantity is that the Ly\(\alpha\) volume emissivity, \(j_\alpha(r)\), increases rapidly toward smaller radii. This causes the total Ly\(\alpha\) luminosity emitted by material enclosed within radius \(R\) (which is \(4\pi \int_{r_\text{min}}^{R} r^2 \, dr \, j_\alpha(r)\)) to depend strongly on the choice of \(r_\text{min}\). Furthermore, \(j_\alpha(r)\) is highly uncertain at small radii, because various effects that are not included in the simulation (e.g. star formation) can affect \(j_\alpha(r)\), \(r_\text{min}\) and the gas’ central density and velocity field. The L\(\alpha\) luminosity plotted in Figure 1 is only affected at the smallest radii by these uncertainties.

The lower left panel of Figure 1 shows that all radii contribute to the total Ly\(\alpha\) luminosity during the early stages of the collapse. However, at later times the density in the inner few kpc builds up (e.g. at time=1.1 Gyr, the number density of hydrogen nuclei is \(\geq 0.01\) cm\(^{-3}\) for \(r \leq 4\) kpc, see Appendix A) which boosts the collisional excitation rate of the Ly\(\alpha\) transition. This causes the central few kpc of the collapsing gas to dominate the total Ly\(\alpha\) cooling luminosity.

Of course, the results presented above are suspicious as they were obtained from a spherically symmetric simulation. In a scenario of hierarchical structure formation halos are build up of mergers of smaller halos that collapsed at earlier times. Gas accretion is therefore likely to occur in dense clumps, which affects the results we obtained above in several ways: (i) Collisions between gas clumps convert the clumps’ kinetic energy (due to infall) into thermal energy, which is then radiated away as cooling radiation; (ii) Clumping can boost the the collisional excitation rate of atomic hydrogen and hence the Ly\(\alpha\) emissivity.

Only (i) affects the predicted surface brightness profile: In the 1-D calculation, gravitational binding energy is mainly converted into kinetic energy of the infalling gas. This kinetic energy must be (partly) released as cooling radiation in the center of the halo (see Birnboim & Dekel 2003, Keres et al. 2005, for more detailed discussions on this topic). Therefore, most of the gravitational binding energy can only be released in the center, which causes cooling radiation emerging from a 1-D simulation to peak too much toward the center. However, Haiman et al. (2000) showed that clumpy accretion also results in surface brightness profile that is peaked towards the center, and that...
the inner 10% of the gas (in radius) emits \( \sim 30\% \) of total Ly\( \alpha \) luminosity. In the calculations of Haiman et al. (2000) gravitational binding energy is emitted continuously while the gas streams towards the center of the halo. Furthermore, 3-D simulations by Kereš et al. (2005) have shown that the gas’ infall speed increases down to \( \sim 0.5 \) virial radii after which the infall velocity slowly decreases (also see Wise & Abel 2007). In this case gravitational potential energy is radiated away in a more compact region than that described by Haiman et al. (2000). Therefore, we conclude that the actual compactness of Ly\( \alpha \) cooling radiation is probably bracketed by the 1-D simulation shown above and the analytic estimate presented by Haiman et al. (2000).

The lack of clumps causes the total Ly\( \alpha \) luminosities shown in Figure 1 to be lower than the estimates presented by Haiman et al. (2000), which only depended only on the energy budget of the gas. Haiman et al. (2000) found that the total Ly\( \alpha \) luminosity due to cooling can be as large as \( 10^{43} - 10^{44} \) erg s\(^{-1}\) in halos in the mass range log\( M_{\odot} / M_{\odot} = 11 - 12 \). The compactness of the emission implies that a cooling blob \( \lesssim 1 \) arcsec in diameter may emit Ly\( \alpha \) luminosities exceeding \( 10^{42} \) erg s\(^{-1}\). This Ly\( \alpha \) luminosity is comparable to that observed high-redshift Ly\( \alpha \) emitting galaxies (e.g. Kashikawa et al. 2006). It is worth pointing out that resonant scattering of Ly\( \alpha \) is not expected to flatten the observed surface brightness profile significantly (Dijkstra et al. 2006, hence these source also appear compact on the sky).

It should be pointed out that in the hierarchical structure formation model, the progenitor halos that merge into the halo of interest, are likely substantially more massive that the minimum halo mass that is capable of cooling gas by collisionally exciting atomic transitions (i.e. halos with \( T_{\text{vir}} \geq 10^4 \) K which corresponds to \( M_{\text{vir}} \gtrsim 10^9 M_{\odot} \)). Hence, gas inside these halos were likely capable of collapsing and forming stars. It is therefore plausible that previously formed stars already exist in the newly formed halo in which gas still needs to cool and collapse to its center. These older stars however are not expected to contribute to the rest-frame UV (and Ly\( \alpha \)) luminosity of the cloud.

3. COOLING RADIATION REDWARD OF LY\( \alpha \)

In the previous section we concluded that the Ly\( \alpha \) luminosity associated with compact cooling gas clouds can be comparable to that of star forming galaxies. In this section we calculate the spectral energy distribution of cooling radiation at wavelengths other than Ly\( \alpha \), and investigate whether this can distinguish a cooling cloud from a star forming galaxy.

3.1. The 2\( \gamma \) Continuum: Luminosity & Spectrum

Yang et al. (2006) found that gas in their simulations becomes self-shielding for densities exceeding \( n \gtrsim 200 n_{\text{hi}} \), where \( n_{\text{hi}} \) is the mean cosmic number density of hydrogen (see their Fig 2). In the absence of a photoionizing background, collisional excitation of hydrogen dominates the total cooling rate for gas temperatures of \( \sim 1 - 3 \times 10^4 \) K (see e.g Fig 1 of Thoul & Weinberg 1995). For higher temperatures the residual neutral hydrogen fraction becomes too small (\( n_{\text{hi}} \lesssim 1 \times 10^{-3} \)) assuming collisional ionization equilibrium, see e.g. House 1964, Hui & Gnedin 1997), and this cooling mechanism is shut off. Even in the 1-D simulation used in §2 which did not include self-shielding, collisional excitation of hydrogen dominates the cooling rate at radii \( \lesssim 10 \) kpc (see Fig 1).

Collisions between electrons and neutral hydrogen atoms mainly excite the \( n = 2 \) states (collisional excitation of the \( n = 3 \) states occurs \( \gtrsim 10 \) times less frequently at the temperatures considered here). The collisional excitation rates from \( 1s \rightarrow 2p \) and \( 1s \rightarrow 2s \) are comparable as the effective collision strengths are comparable, \( \Omega(1s, 2s)/\Omega(1s, 2p) = 0.6 - 0.5 \) for \( T_{\text{gas}} = 1 - 2 \times 10^4 \) K (Osterbrock & Ferland 2006). Table 3.16, the temperature dependence of this ratio is weak. Transitions from \( 2s \rightarrow 1s \) may only take place when two photons are emitted that have a combined energy of 10.2 eV (Breit & Teller 1940). This two-photon process results in the following spectrum

\[
f_{2\gamma}(\nu) = \frac{\Omega(1s, 2s)}{\Omega(1s, 2p)} N_{\text{Ly\alpha}} h\nu \phi(\nu/\nu_{\alpha}) d\nu/\nu_{\alpha}.,
\]

where \( N_{\text{Ly\alpha}} \) is the rate at which Ly\( \alpha \) photons are emitted, \( \phi(\nu/\nu_{\alpha}) d\nu/\nu_{\alpha} \) is the probability that 1 photon is emitted in the frequency range \( \nu \pm \nu_{\alpha}/2 \), which can be found in Spitzer & Greenstein (1951). The spectral energy distribution according to Eq (1) is shown in Figure 2. The units of \( f_{\gamma} \) are chosen such that \( \int d\nu f_{2\gamma}(\nu) = [\Omega(1s, 2s)/\Omega(1s, 2p)] f_{\alpha}/T_{\alpha} \). Here, \( f_{\alpha} \) is the observed Ly\( \alpha \) flux and, \( T_{\alpha} \) is the fraction of Ly\( \alpha \) photons that is transmitted to the observer through the IGM (see below). For example, Figure 2 shows that the peak flux density in the two-photon continuum \( f_{\gamma,\max} = 2 \times 10^{-32} f_{\alpha,17}(0.2/T_{\alpha}) \) erg s\(^{-1}\) cm\(^{-2}\) Hz\(^{-1}\), where \( f_{\alpha} \equiv f_{\alpha,17} \times 10^{-17} \) erg s\(^{-1}\) cm\(^{-2}\). Also shown is a schematic representation of the Ly\( \alpha \) line (its shape is arbitrary).

Other process which contribute to wavelengths redward of Ly\( \alpha \) include recombination and bremsstrahlung cooling. As already mentioned however, in cooling gas at \( T \lesssim 3 \times 10^4 \) K both of these processes are negligible compared to collisional excitation of hydrogen (see § 3.2 for a more detailed discussion), and their contribution to the continuum spectrum can be safely ignored.

The prominence of the Ly\( \alpha \) line relative to its continuum is

3 Collisional deexcitation of the 2s state suppresses the 2\( \rightarrow \) emissivity by a factor of \((1 + 2n_{p}/n_{e})^{-1}\), where \( n_{e} \) is \( 1.5 \times 10^{3} \) cm\(^{-3}\) is the critical density of the 2\( \rightarrow \) transition, and \( n_{p} \) is the number density of protons (Osterbrock & Ferland 2006). Therefore, only gas with densities exceeding \( n_{e} \) is expected to emit the two-photon continuum at levels less than that calculated above. These high densities are never reached in the simulation (see Appendix A) and collisional deexcitation is not important in the context of this paper.
quantified by the equivalent width (EW) which is defined as \( \text{EW} = L_\alpha / f_\alpha \). Because of the strong wavelength dependence of the continuum between \( \lambda = 1216 - 1600 \) Å, the precise EW depends on the wavelength at which the continuum flux density is measured. This is shown in Figure 3 which shows the emitted rest frame Ly\( \alpha \) EW of cooling radiation as a function of the wavelength (rest frame) at which it is measured. The EW diverges when \( \lambda \rightarrow 1216 \) Å, as the continuum flux density approaches zero. Note that the observed rest frame EW is likely to be a factor of \( \approx 5 - 10 \) lower because of scattering of Ly\( \alpha \) photons in the IGM (see text).

Figure 3.— The emitted rest frame Ly\( \alpha \) equivalent width (EW) of cooling radiation as a function of the wavelength (rest frame) at which the continuum is measured. The EW diverges when \( \lambda \rightarrow 1216 \) Å, as the continuum flux density approaches zero. Note that the observed rest frame EW is likely to be a factor of \( \approx 5 - 10 \) lower because of scattering of Ly\( \alpha \) photons in the IGM (see text).

3.2. Prospects for Using 2-\( \gamma \) Emission as a Tracer of Cooling Clouds

3.2.1. Cooling Clouds and the 2-\( \gamma \) Continuum

The fate of the gas as it approaches the center of the dark matter halo is not known (see Keres et al. 2005, for more discussion on this). The gas may be slowed down gradually, or may smoothly join a rotating gaseous disk that formed in the center of the dark matter halo. In both these scenarios the gas would remain cold and would emit the spectrum shown in Figure 2.

However, this is not the case when gas approaches \( r = 0 \) with velocities of order \( \sim 100 \) km s\(^{-1}\) (as was the case in the 1-D simulation used in § 2). When the gas crashes into the center, it is shock-heated to \( T \sim 10^5 \) K and emits bremsstrahlung up to energies of \( \sim 100 \) eV. This ionizing radiation creates an H II region of \( \lesssim 1 \) kpc because of the large gas densities in the center of the halo (Birnboim & Dekel 2003). This ionizing radiation could furthermore doubly ionize helium.

This recombing gas may emit a spectrum that is very similar to that shown in Figure 2. In Figure 4 the solid line shows the spectrum emitted by gas assuming case-A recombination and a gas temperature of \( T = 2 \times 10^4 \) K. In this case the bound-free (free-free) emissivity is given by \( \epsilon = 5.3 \times 10^{-25} \text{ erg s}^{-1} \text{ cm}^{-3} \) (e.g. Osterbrock & Ferland 2006). Furthermore, the total emissivity in the two-photon continuum is \( \epsilon \sim 5.0 \times 10^{-25} \text{ erg s}^{-1} \text{ cm}^{-3} \) Osterbrock & Ferland (2006). Table 4.1, and we used that \( \epsilon_{2\gamma} \sim 0.5 \epsilon_{(Ly\alpha)} \). It is noted that when helium is doubly ionized inside the H II region, and/or for higher gas temperatures, more continuum emission is emitted at \( \lambda < 2000 \) Å (as well as a He II H\( \beta \) line at \( \lambda = 1640 \) Å), which would weaken the appearance of the dip. The dotted line shows the spectrum resulting from bound-bound transitions only (which corresponds exactly to the case shown in Fig 2). Technically the Ly\( \alpha + 2-\gamma \) radiation is not cooling radiation itself, but is emitted by the cooling cloud as a by-product of recombination cooling radiation (see § 1). Clearly, recombing gas at \( T < 2 \times 10^5 \) K emits a spectrum of similar to that of ‘pure’ cooling radiation, especially at wavelengths where the spectrum differs from that emitted by star forming galaxies, \( \lambda = 1200 - 2000 \) Å.

3.2.2. Star Forming Galaxies and the 2-\( \gamma \) Continuum

Of course, recombinig H II regions (of primordial composition) surrounding stars or quasars emit the same spectrum as that shown in Fig 2. However, in observed galaxies this nebular emission is subdominant to the continuum radiation from stars/quasars, which does not exhibit the dip shown in Figure 4. A notable exception is discussed by Schaerer (2002), who shows that nebular emission dominates the stellar continuum at wavelengths redward of Ly\( \alpha \) during the first 1-2 Myr in metal-free galaxies that are forming stars according to top-heavy initial mass function (IMF). Hence, these primordial star forming galaxies also exhibit the two-photon dip in their spectra during the first 1-2 Myr of their lifetime (see Fig 5 of Schaerer 2002). On the other hand, these galaxies also emit He III recombination lines such as the He 1640 line, which is not the case for cooling radiation when the gas does not get shock heated to \( T \gtrsim 10^5 \) K (as was discussed above in § 3.2.1).
shown (free-bound and bound-bound transitions. The of cooling gas (Fig 2). Clearly, the spectra of recombining and cooling gas are becomes efficient when densities exceed tail by Spaans & Silk (2006). However, this mechanism only suppressed strongly. This process has been studied in more de-

3.2.3. The Impact of Lyα Radiative Transfer

It is worth pointing out is that for sufficiently large columns of neutral hydrogen gas ($N_{\text{HI}} \gtrsim 10^{22}$ cm$^{-2}$), Lyα photons scatter so frequently that collisional deexcitation from the 2p level may become important, and the Lyα cooling channel may be suppressed strongly. This process has been studied in more detail by Spaans & Silk (2006). However, this mechanism only becomes efficient when densities exceed $\gtrsim 10^5$ cm$^{-3}$, which is much larger than the highest densities in the simulation shown in Figure 1 (see Fig 5 in Appendix 5). Furthermore, this effect enhances the expected 2-$\gamma$ continuum relative to the Lyα line, and if Lyα were ever detected from these ultracompact cooling cores, then the associated 2-$\gamma$ flux is relatively brighter and thus easier to detect.

So far, the role of dust in the Lyα radiative transfer has not been discussed. One might expect little dust to exist in gas that is still cooling to form stars. However, as mentioned in § 2 in models of hierarchical structure formation, star formation is expected to have occurred in the less massive progenitor halos which merged into the halo of interest. Thus, dust is expected to exist in the cooling cloud. Dust would redden and suppress the UV-continuum, but to quantify this effect theoretically is difficult. Empirically, Bouwens et al. (2006) found the rest-frame UV continuum of $z = 6$ Lyman Break Galaxies (LBGs) to be suppressed by dust by a factor of only $\sim 1.4$. It is reasonably to expect the progenitor halos not to contain more dust than these more massive -and hence probably more evolved- LGs, and we therefore do not expect dust attenuation of continuum cooling radiation to be significant 4.

The impact of dust on Lyα is less clear. In principle, resonant scattering enhances the total distance Lyα photons travel through a medium, which makes them more prone to destruction by dust. In this case, the 2-$\gamma$ continuum would be enhanced relative to Lyα and would therefore be easier to detect. On the other hand, Lyα may preferentially avoid destruction by dust 4 Gnedin et al. (2008) found the mean escape fraction of ionizing radiation in (adaptive mesh refinement) hydrodynamical simulations of high-redshift galaxies to be $f_{\text{esc}} \sim 1\%$. However, the opacity to ionizing photons in these simulations was found to be dominated by neutral atomic hydrogen and helium.

in a two-phase medium in which dust resides in cold ($T \sim 10^4$ K) neutral denser clumps embedded in a hot medium (Neufeld 1991; Hansen & Oh 2006). In this scenario, the 2-$\gamma$ continuum would be attenuated (by a factor of $\lesssim 1.4$ as we argued above), but the Lyα would be freely transmitted. It is therefore good to keep in mind that our quoted Lyα luminosities have not corrected for dust attenuation, but that this correction is not necessarily needed.

4. DISCUSSION & CONCLUSIONS

The collapse and condensation of baryons into the center of their host dark matter halos is accompanied by emission of radiation that may be detectable as compact UV-continuum and Lyα emission with Lyα luminosities as high as $\sim 10^{42} - 10^{43}$ erg s$^{-1}$ in halos of mass $M = 10^{11} - 10^{12} M_\odot$. These luminosities are comparable to those detected in narrowband surveys for redshifted Lyα emission.

Cooling clouds emit continuum radiation redward of Lyα that is dominated by two-photon transitions from 2$s$ to 1$\gamma$. The emitted Lyα equivalent width (EW) relative to this continuum is EW $\sim 1000 - 1300$ Å (rest-frame), which is comparable to the EW emitted by galaxies forming either metal-poor or very massive stars. The IGM is likely to transmit only $\lesssim 30\%$ of this Lyα flux and the observed rest frame equivalent width is therefore EW $\lesssim 400$ Å. This is comparable to the observed equivalent widths among high-redshift Lyα emitting galaxies. It is therefore possible that existing surveys have detected compact Lyα emission that was emitted by cooling clouds.

Because of the dominance of the two-photon continuum, cooling clouds emit a spectrum that peaks at $\lambda \sim 1600$ Å (rest-frame), and sharply drops down to $\lambda = 1216$ Å. This peculiar spectral shape distinguishes cooling clouds from observed young star forming galaxies, whose continuum is dominated by radiation from stars/quasars (e.g. Stanway et al. 2005). However, this is not true for metal-free galaxies that are forming stars according to top-heavy initial mass function. In these primordial galaxies, nebular emission may dominate the continuum redward of Lyα during the first few Myr of their lifetime (Schaerer 2002). On the other hand, these galaxies also emit He III recombination lines such as the He 1640 line, which is not the case for cooling radiation when the gas is not shock heated to $T \gtrsim 10^4$ K (see § 3.2). Furthermore, deeper Lyα observations of compact cooling clouds should find weaker emission on larger scales. However, the same applies to Lyα emitting star forming galaxies, which are likely surrounded by faint Lyα halos due to resonant scattering in the surrounding IGM (e.g. Loeb & Rybicki 1999, Dijkstra & Loeb 2003). This scattered Lyα emission is not accompanied by continuum radiation redward of the Lyα line, which could distinguish it from spatially extended Lyα cooling radiation (polarimetry may provide additional insights, see Dijkstra & Loeb 2008).

Ongoing and future surveys for redshifted Lyα emission aim to detect Lyα emitters out to redshifts as high as $z \sim 6 - 12$ (e.g. Stark et al. 2007; Nilsson et al. 2007, and references therein). These observations will provide new insights into the epoch of reionization and galaxy formation at high redshift. Primordial galaxies -like cooling clouds- may emit very large EW Lyα emission lines (e.g. Schaerer 2003). In order to measure the EW of the Lyα line and to determine whether primordial galaxies are detected, the continuum redward of Lyα must be detected. This is challenging; if the observed flux in the Lyα line is $f_{\alpha,17}$ (in units of $10^{-17}$ erg s$^{-1}$ cm$^{-2}$) and its equivalent

![Figure 4](image_url)
width is EW (in Å), then the AB-magnitude of the continuum is $m_{AB} = 30.4 - 2.5 \log T + 2.5 \log (EW/200)$. For comparison, the Hubble Ultra Deep Field reached an $8 - \sigma$ limiting magnitude in the $z'$ filter of $z'_{AB} = 28.5$ (Bunker et al. 2004).

Detecting both the Ly$\alpha$ line and the continuum is not only desirable for identifying primordial galaxies. An additional advantage of combining Ly$\alpha$ and continuum measurements of high-redshift galaxies is that it can greatly improve the constraints on the epoch of reionization (e.g. Kashikawa et al. 2006; McQuinn et al. 2007) over constraints obtained using Ly$\alpha$ alone.

The work presented in this paper suggests that if primordial galaxies can be detected and identified, then the same applies to cooling clouds. Moreover, primordial galaxies may only be luminous in Ly$\alpha$ for $\approx 10$ Myr (Malhotra & Rhoads 2002; Dijkstra & Wyithe 2007). Cooling clouds could be luminous in Ly$\alpha$ for longer than 10 Myr, which would make them more easily detectable than primordial galaxies. The discovery of two-photon dominated Ly$\alpha$ emitters would offer us an exciting glimpse of the process of gas cooling in newly forming galaxies, or of star formation in the first primordial galaxies.

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APPENDIX A
OUTPUT FROM THE SIMULATION

Two snapshots of the simulation used in §2 are shown in Figure 5. The radial dependence of the number density of H-nuclei (n_H, upper panel), the fraction of neutral atomic hydrogen gas (x_HI = n_HI/n_H, central panel), and the gas temperature (T, lower panel) are shown at time=0.9 Gyr (solid lines) and time=1.1 Gyr (dashed lines). Snapshots of the simulation at these times were also shown in Figure 1.

Figure 5 shows that the gas temperature in the inner 10 kpc is $T_{gas} < 3 \times 10^4$ K at both times, which corresponds to the temperature regime where collisional excitation of hydrogen dominates gas cooling. Note that the snapshot at time=1.1 Gyr shows some strange behaviour at $r < 2$ kpc. This is related to the formation of a shock that is produced by the gas that is radially moving inwards at a supersonic speed, which causes the gas to shock-heat to $T > 10^5$ K. As was mentioned in §2, the simulation results are suspicious in these innermost regions.

Lastly, we point out that the gas density is well below the critical density, $n_c = 1.5 \times 10^4$ cm$^{-3}$, at which collisional deexcitation of the 2s-state becomes important.

APPENDIX B

LY$\alpha$ RECOMBINATION VS. LY$\alpha$ COOLING RADIATION

Here we compare the Ly$\alpha$ cooling rate due to collisional excitation, $\Lambda_{Ly\alpha}$, with the Ly$\alpha$ emission rate due to recombination, $R_{Ly\alpha}$. Their ratio is given by

\[ R = \frac{\Lambda_{Ly\alpha}}{R_{Ly\alpha}} = \frac{7.3 \times 10^{-10} n_{H} \exp\left(-\frac{118000}{T}\right)}{0.68 \times \frac{\tau_{rec, \alpha}}{\tau_{\alpha}} \times \frac{\nu_{\alpha}}{\tau_{H}} \times (1.0 - \tau_{H})}. \]  

(B1)

where $\tau_{rec, \alpha} = 2.6 \times 10^{-13} (T/10^4 K)^{-0.7} \text{cm}^2 \text{s}^{-1}$ is the case-B recombination coefficient. For $T = 3 \times 10^4$ K we find $R \approx 1.0 \times (\tau_{H}/10^{-10})$ (for $\tau_{H} \ll 1$), and $R$ increases with $T$. That is, even in a highly ionized plasma, a significant fraction of the emitted Ly$\alpha$ photons are produced following collisional excitation of the much rarer neutral hydrogen atoms.
Fig. 5.— Simulation outputs at time=0.9 Gyr (solid lines) and time=1.1 Gyr (dashed lines) are shown. The upper/middle/lower panel shows the radial dependence of the gas density/neutral fraction of atomic hydrogen/temperature. These quantities were used to compute the cooling rates shown in Figure 1. The snapshot at time=1.1 Gyr shows that the simulation behaves strangely in the inner 2 kpc (see text).