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LYMAN-ALPHA BLOBS NUMBER DENSITY AND COLD GAS ACCRETION

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Abstract. In this work we attempt to model the observed evolution in comoving number density of Lyman-alpha blobs (LABs) as a function of redshift. Our model assumes that cooling radiation (CR) from the intergalactic gas is the main source of LABs emission. We have used the evolution of distribution of halo masses from a dark matter (DM) cosmological simulation and cold mode gas accretion rates as a function of halo mass and redshift from hydrodynamical simulation. In this work we present our results.

1. INTRODUCTION

Lyman-alpha blobs (LABs) are very luminous ($\sim 10^{43}$-10^{44} erg/s) and very extended (with diameters of $\sim$ 50-100 kpc and more) regions of Lyα emission, which are radio quiet. They are observed at a range of redshifts $z \sim$ 1-6.6, but the bulk of objects currently known is found between $z \sim$ 2-3 (e.g. Steidel et al. 2000; Matsuda et al. 2004, Yang et al. 2010; Erb et al. 2011). A search for LABs at $z = 0.8$ has found none (Keel et al. 2009), suggesting that their comoving number density (N_{LAB}) sharply decreases from $z \sim$ 2-3 to $z \sim$ 0.8, and that LAB might be only a high redshift phenomenon (see also Barger et al. (2012) and Prescott (2009)). LABs are rare (with comoving number density $\sim 10^{-6}$ Mpc^{-3} - 10^{-4} Mpc^{-3}) and preferentially found in overdense regions (e.g. Yang et al. 2010), which indicates that LABs could be sites of formation of most massive galaxies.

It is still not clear what is the mechanism that powers the intensive Lyα emission of LABs. One of the proposed mechanisms of emission is cooling radiation from cold streams of gas accreting onto galaxies (CR; e.g. Dijkstra & Loeb 2009). Numerical simulations show that not all the gas that is accreted onto galaxies is shock heated to roughly the virial temperature. Some fraction of the gas maintains a temperature of $T < 2.5 \times 10^5$ K and is accreted onto galaxies in the form of filamentary streams (e.g. Kereš et al. 2009). This is the cold mode gas accretion. While the cold gas is streaming towards the dark-matter halo potential well, gravitational binding energy is released and the hydrogen atoms are excited, followed by cooling emission of Lyα (e.g. Haiman et al. 2000). In cases where LABs are not associated with other sources that are powerful enough to explain the observed Lyα luminosities, CR could play a dominant role (Nilsson et al. 2006; Smith et al. 2008; Matsuda et al. 2006; Saito et al. 2006).

Previously a number of authors have created simulations and analytical models which try to explain LABs emission through the cooling radiation alone. Some of them simulated LABs with similar Lyα luminosities, Lyα line widths, and number densities as the observed LABs at $z = 3.1$ (e.g. Dijkstra & Loeb 2009, Goerdt et al. 2010, Rosdahl & Blaizot 2012), but others concluded that it is difficult to explain LAB radiation with CR (e.g. Faucher-Giguère et al. 2010, Cen and Zheng 2012). These results depend on detailed modelling of Lyα cooling radiation (such as radiative transfer and self-shielding) and on the resolution of the simulation.

In this work we attempt to once again investigate if CR can be the main source of LAB energy, but now including the whole range of redshifts where LABs are observed $z \sim$ 0-7, and using a simple (analytical) model in which we calculate Lyα emission from the released gravitational potential energy and from the cold gas accretion rates.

2. MODEL

Our model assumes that cooling radiation (CR) from the intergalactic gas is the main source of LAB emission. We have used the evolution of distribution of halo masses from a dark matter (DM) cosmological simulation and cold mode gas accretion rates as a function of halo mass and redshift from hydrodynamical simulation from Faucher-Giguère et al. (2011) (FG11). For every halo we calculated Lyα luminosity from the released gravitational potential energy.

Now we present an overview of equations we have used for computing Lyα luminosity, which are also derived in Goerdt et al. (2010) (G10). While cold gas is streaming from virial radius $R_{\rm vir}$ to some radius r_0 in a halo, gravitational energy is released. Lyα radiation originates from a fraction f_c of this energy that is heating the cold streams, while the rest is converted in kinetic energy or is heating the hot streams of the gas. A fraction f_α of this energy represents the radiation which we see at the Lyα line. It includes absorption by intergalactic medium and absorption by dust or HI inside a halo. If we assume that cold gas accretion rate $\dot{M}_c$ and the velocity of its accretion are roughly constant from $R_{\rm vir}$ to r_0 (as did G10; however, readers should be cautioned that later work of FG11 showed that $\dot{M}_c$ may in fact drop at smaller radii.), then the observed Lyα luminosity is

$$L_{Ly\alpha} = f_\alpha f_c \dot{M}_c |\Delta\Phi(R_{\rm vir}, r)|, \tag{1}$$

where $\Delta\Phi(R_{\rm vir}, r)$ is a potential difference between virial radius $R_{\rm vir}$ and some radius r in a halo.

In our model we have used FG11 estimates of cold gas accretion rate, and fitted a polynomial which describes $\dot{M}_c$ as a function of halo mass $\log M$ and redshift $\log(1+z)$. Further details are described in our forthcoming paper in MNRAS.

For Navarro, Frenk & White (1997) halo mass density profile it can be shown that

$$|\Delta\Phi(R_{\rm vir}, r)| = {V_{\rm vir}}^2 \frac{C}{A_1(C)} \left[\frac{\ln(1+x)}{x} - \frac{\ln(1+C)}{C} \right], \tag{2}$$

where C is a concentration parameter, $x = Cr/R_{\rm vir}$, $A_1(x) = \ln(x+1) - x/(x+1)$, and $V_{\rm vir}$ is the virial velocity, $V_{\rm vir} \simeq 236\,{\rm km\,s^{-1}} {M_{12}}^{1/3} {(1+z)_4}^{1/2}$ (Goerdt et al. 2010).

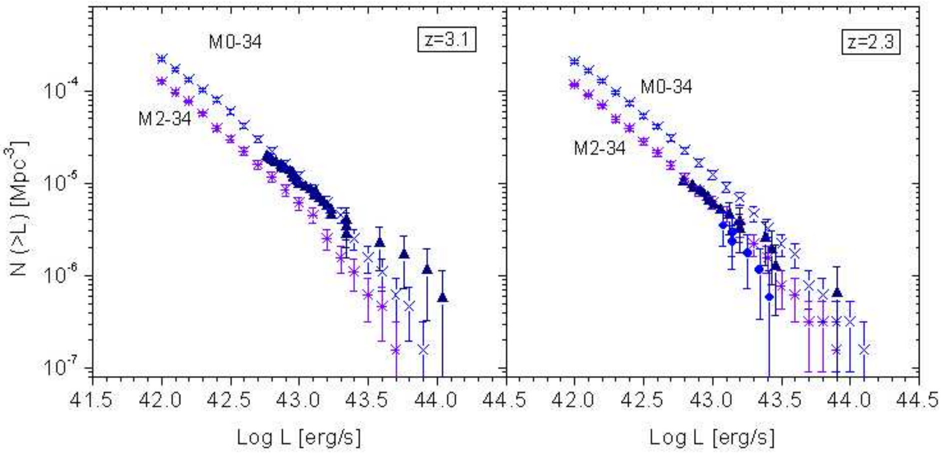

Figure 1: Luminosity function at $z = 3.1$ (left) and $z = 2.3$ (right), for cases M0-34 (blue x) and M2-34 (violet *). Data from observations: Matsuda et al. (2004) ($z = 3.1$; triangles), Yang et al. (2010) ($z = 2.3$; triangles), Erb et al. (2011) ($z = 2.3$; circles). Poisson errors for our model and for observations are indicated, except for less luminous LAB.

We use estimate of average concentration parameter from Bullock et al. (2001): $C \approx 3(M_{\rm vir}/10^{12}{\rm M}_\odot)^{-0.13}((1+z)/4)^{-1}$.

Now, for given values of f_α, f_c and r_0 one can determine luminosity of a halo at a given mass and redshift. We will assume that these parameters are equal for all halos, at all redshifts. The r_0 is radius inside a halo until which cooling luminosity is significant. Near the halo center cold gas accretion rate is smaller and dust near the galaxy in the halo center absorbs some fraction of Lyα photons. In this work we determine luminosities for $f_\alpha f_c = 0.34$, which is the value G10 used to reproduce observed values, for luminosities for 2 cases:

1) M0-34: $f_\alpha f_c = 0.34$, $r_0 = 0$ (accretion to the center of halo), and

2) M2-34: $f_\alpha f_c = 0.34$, $r_0 = 0.2R_{\rm vir}$ (accretion which does not include the central galaxy at $z \sim 2-3$),

and compare them with observations. We also determined N_{LAB} for a few other values of these parameters.

3. RESULTS AND COMPARISON WITH OBSERVATIONS

In this section we present our luminosity functions at $z = 2.3 - 3.1$, and comoving number densities at a redshift range $z = 0 - 7$. Observed number densities are previously corrected for the density contrast of Lyman-alpha emitting galaxies in the observed volume (this is further explained in our forthcoming paper in MNRAS, in preparation). Because of the large volume of our DM simulation, we will proceed with the assumption that our DM simulation results are indicative of an average number density of LABs.

3. 1. LUMINOSITY FUNCTIONS AND CONSTRAINING A FREE PARAMETER

In Figure 1 we compare cumulative luminosity functions (LF) at $z = 3.1$ and $z = 2.3$ from our model (for cases M0-34 and M2-34) and from observations (for Matsuda et al. (2004), Yang et al. (2010), and Erb et al. (2011)). For $z = 3.1$ we see that LF from our model for accretion to the center is in good agreement with observations at luminosities $L < 10^{43.5}$ erg/s. We note that for different values of $f_\alpha f_c$ we could get different values in LF, but still the same slope. Agreement between the slopes of LF from our model and from observations could indicate that cold gas accretion has an important role in luminosity of LAB, or that another mechanism of luminosity is related to mass of halo in similar way. For example, besides cold gas accretion $\dot{M}_c$, also star formation rate could be related in similar way with halo mass.

For $L > 10^{43.5}$ erg/s we get smaller values of LF than observed. This could partially be because of cosmic variance, as the most luminous LAB are rare, therefore the error bars are largest for the most luminous LABs and for larger observed volumes we would get smaller observed LF. The other possibility is that evolution of more luminous LAB is more rapid, and that there is additional mechanism of energy, so observed luminosities are larger than that from our model, which includes only cold gas accretion.

For $z = 2.3$ we get similar conclusions, but now we obtain agreement for different parameters, i.e. for accretion to $0.2R_{\mathrm{vir}}$. If we assume that our comparison with observations is correct, this difference could be explained if: 1) the rate $\dot{M}_c$ is smaller at $r < R_{\mathrm{vir}}$ than at R_{vir}, more significantly as z decreases, 2) dust absorption (in the vicinity of galaxy) is larger at lower z, 3) f_c is smaller at lower z.

3. 2. COMOVING NUMBER DENSITY AS A FUNCTION OF REDSHIFT

We assume that all halos with $L_{Ly\alpha} > 10^{43}$erg/s, $d > 50$kpc are identified in observations as LAB, and compare its comoving number density (N_{LAB}) from our model and from observations. However, to estimate LAB diameters from a DM simulation properly would be difficult, as we would need to account for irregular LAB shape and estimate of surface brightness distribution with radius from the LAB center. For now we will just estimate N_{LAB} from the ratio of number density of 1) LAB with $L > 10^{43}$ erg/s (N_{43}), and 2) LAB with $L > 10^{43}$ erg/s and $d > 50$ kpc. We find this ratio in surveys from Matsuda et al. (2004) at $z = 3.1$ and in two surveys from Yang et al. (2010) at $z = 2.3$, and obtain that it is equal to ~ 2. We estimate N_{LAB} in our model as $N_{LAB} \sim N_{43}/2$.

In Figure 2 we compare N_{LAB} from our model for cases M0-34 and M2-34 (dotted lines), with the observed ones. We retrieve good agreement between observations and our model for case M0-34 at $z \sim 3$ and for case M2-34 at $z \sim 2.3$ (as for luminosity functions). All observed number densities at $z = 2.3$ are similar and in agreement with that from our model (accounting for errors), with exception of number density for Palunas et al. (2004), which is somewhat lower. At $z \sim 4$ for definition of LABs as $L_{Ly\alpha} > 10^{43}$erg/s our N_{LAB} for case M0-34 is almost identical to that from survey of Saito et al. (2006).

However, for both of these cases N_{LAB} from our model falls below observed N_{LAB} at high redshifts, and above at lower redshifts. At redshift $z = 0.8$ our N_{LAB} for M0-34 and M2-34 are at least $\sim$ 3-6 times larger than observed, and with corrections for overdensity of $\delta = 1$ and $\delta = 6$ larger by a factor of $\sim$ 5-10 and $\sim$ 20-45, respectively.

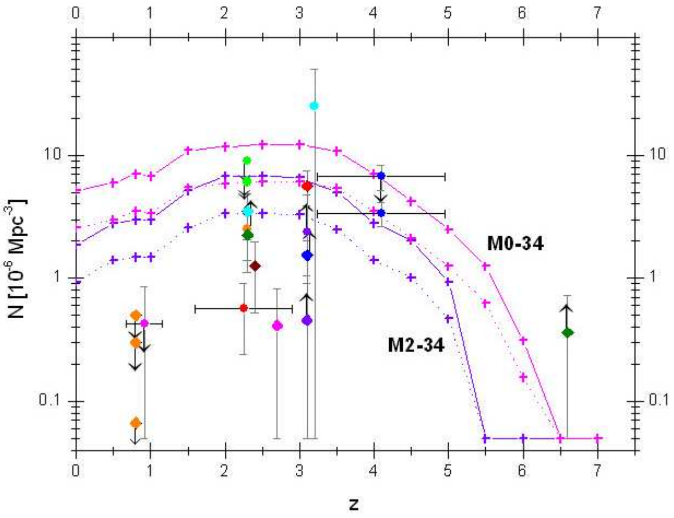

Figure 2: Comparison of comoving number densities of LABs from our model and from observations. Solid lines: N_{43} from our model for cases M0-34 (rose lines) and M2-34 (violet lines). Dotted lines: our estimate of N_{LAB}. At redshifts in which there are no LAB in our model we set $N = 0.05 \times 10^{-6}\mathrm{Mpc}^{-3}$. Symbols are data from observations. At $z \sim 2.3$ these are, from the largest to the smallest number densities: Yang et al. 2010 (upper limits for three fields; light green), Erb et al. 2011 (light blue), Yang et al. 2009 (orange), Yang et al. 2010 (light green), Palunas et al. 2004 (dark red), Prescott (2009)(red). At $z \sim 3.1$: Nilsson et al. 2006 (light blue), Matsuda et al. 2004 (red), Matsuda et al. 2011 (violet), Matsuda et al. 2011 (dark blue), Matsuda et al. 2009 (violet). At $z = 2.7$: Prescott et al. 2008 (rose). At $z \sim 1$: Keel et al. 2009 (not corrected for density contrast), Barger et al. 2012 (rose), Keel et al. 2009 (orange, with different assumptions of density contrast). At $z \sim 3-5$: Saito et al. 2006 (dark blue); we also displayed densities divided by 1.7, 2, and 2.5. At $z = 6.6$: Ouchi et al. 2009 (dark green).

At redshift $z = 6.6$ we don't find LAB from our model for both cases, which is contrary to observations. For $f_\alpha f_c = 1$ our N_{LAB} are somewhat above observations (of one observed LAB at $z = 6.6$), and for $f_\alpha f_c = 0.1$ our N_{LAB} at $z \sim 1$ are still above the observations. This indicates that it is difficult to explain LABs with emission only from CR at a range of redshifts for a constant unknown parameters, but we need more detailed modelling in order to obtain more precise conclusions.

4. DISCUSSION AND CONCLUSIONS

For constant parameters, we obtained a good agreement between the slopes of luminosity functions from our model and from observations at $z = 3.1$ and $z = 2.3$, which could indicate that CR has an important role in luminosity of LABs, or that mechanism of emission is related to mass of halo in a similar way. However, the predicted comoving number density of LAB in our model falls below observed density at high redshift and above at lower redshifts, which could indicate that CR is in fact not the main source of energy of LAB at all redshifts and masses, for constant $f_\alpha f_c$. However, there are still many uncertainties in our model. Some of them are: 1) cold gas accretion rates are actually lower at smaller radii inside a halo, and their decrease along a halo radius is more significant at lower redshifts; 2) with detailed estimate of LABs emission and diameter above some surface brightness threshold our results could change; 3) factor f_c could change with redshift; 4) factor f_α could decrease with redshift if absorption by dust is significant in LABs and if it has more important role at low redshifts.

Our subsequent paper in MNRAS includes a more detailed model of Lyα emission from the cooling radiation, in which we estimate gravitational potentials directly from the dark matter simulation, we include dependence of cold gas accretion rates on radius inside a halo, we include propagation of Lyα photons through the intergalactic medium, and we accounted for Lyα emission just above some surface brightness threshold.

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