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Mass-to-light Ratio of Lyα Emitters: Implications of Lyα Surveys at Redshifts $z = 5.7$, 6.5, 7, and 8.8

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Abstract. We present a simple, relatively model-independent method to interpret the galaxy number count data at $z > 6$. The only free parameter is a mass-to-"observed light" ratio, M_h/L_{band}, where M_h refers to the total mass of the host halo, and L_{band} refers to the observed luminosity of the source. For narrow-band surveys, L_{band} is simply related to the intrinsic Lyα luminosity with a survival fraction of Lyα photons, α_{esc}. The mass-to-"bolometric light", M_h/L_{bol} , can also be found, once the metallicity and initial mass function of stellar populations are given. We find constraints on the mass-to-light ratio of Ly-alpha emitters from $5.7 < z < 8.8$ of $(M_h/L_{bol})\ (\alpha_{esc}\varepsilon^{1/\gamma})^{-1} = 21-38$, $14-26$, and $9-17$ for $Z = 0$, $1/50$, and 1 $Z_\odot$, respectively, where ε is the duty cycle and $\gamma \sim 2$ is the local shape of the cumulative luminosity function. Therefore, Lyα emitters are consistent with either starburst galaxies ($M_h/L_{bol} \sim 0.1-1$) for reasonable values of the Lyα survival fraction, $\alpha_{esc}\varepsilon^{1/\gamma} \sim 0.01-0.05$, or normal populations ($M_h/L_{bol} \sim 10$) if a good fraction of Lyα photons survived. We find no evidence for the end of reionization from current survey observations. The data are consistent with no evolution of intrinsic properties of Lyα emitters or neutral fraction in the intergalactic medium. We also show that the lack of detections at $z = 8.8$ does not rule out the high-z galaxies being the origin of the excess near infrared background.

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INTRODUCTION

It is very likely that there is significant star formation above $z > 6$. With the introduction of new, more powerful telescopes and deep field searches, an interesting question arises: do these first stars form galaxies that are bright enough to be seen today? We present a simple method to calculate the luminosity function of high-z galaxies, and compare this with the results of Lyα searches to constrain properties of Lyα emitters.

A SIMPLE MODEL OF GALAXY COUNTS

The simplest way to predict the cumulative luminosity function of galaxies is to count the number of haloes available in the universe above a certain mass,

$$\int_{F_{limit}}^{\infty} \frac{d^2N}{dF\,d\Omega} dF \approx \Delta z \frac{d^2V}{dz d\Omega} \int_{F_{limit}}^{\infty} \frac{dn}{dM_h} \frac{dM_h}{dF} \vartheta(M_h - M_{min}(z)) dF. \tag{1}$$

where dn/dM_h the comoving number density of haloes per unit mass range, $\Delta z \frac{d^2V}{dz d\Omega}$ multiplied by the field size is the volume of the survey, and M_h is the halo mass. Not all dark matter haloes will be forming stars - only haloes with a mass above some critical minimum mass (M_{min}). This is represented by the function $\vartheta(M_h - M_{min}(z))$, which is zero if the halo mass is smaller than M_{min} and unity if it is larger than or equal to M_{min}.

Relating the luminosity to the flux, equation (1) can be rewritten with respect to M_h/L_{band}:

$$\int_{F_{limit}}^{\infty} \frac{d^2N}{dF\,d\Omega} dF = 4\pi d_L^2(z) \frac{dV}{dz d\Omega} \Delta z \Delta \nu_0 \frac{M_h}{L_{band}} \int_{F_{limit}}^{\infty} \frac{dn(M_h(F))}{dM_h} dF \times \vartheta(M_h - M_{min}(z)). \tag{2}$$

where $\Delta\nu_0$ is the bandwidth of the instrument, d_L is the luminosity distance, and L_{band} is the observed luminosity within a certain bandwidth of the instrument. M_h/L_{band} is the parameter that should be measured from the observational data directly.

NARROW-BAND LYα SURVEYS: OBSERVATIONS

In this paper we use the observational data from six narrow band Lyα searches. Two surveys at $z = 5.7$ and $z = 6.56$ were taken at the Subaru telescope using the Suprime-Cam. At $z = 5.7$, there were 34 Lyα emitters [10] and at $z = 6.56$, there were 17 Lyα emitters confirmed [11, 5]. From these detections, they were able to fit a Schechter luminosity function. The Large Area Ly-

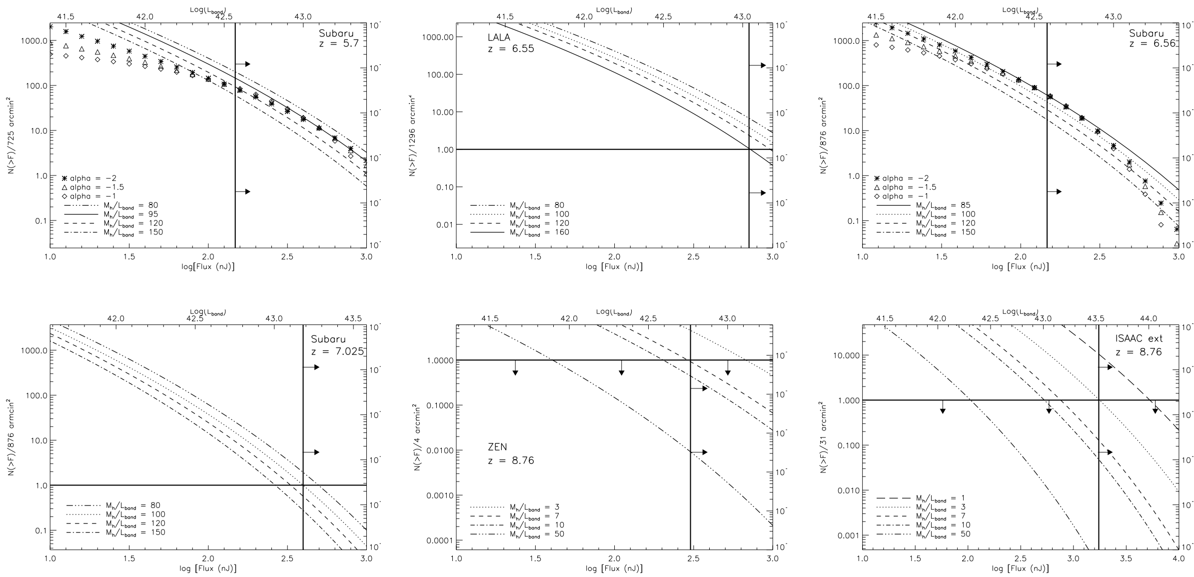

FIGURE 1. The observed luminosity function of Lyα emitters constrains their mass-to-"observed light" ratio. Each panel shows the cumulative number of sources detected in each field above a certain flux, $N(>F)$. (The flux limits of each survey are indicated by the vertical lines with right arrows.)

man Alpha (LALA) survey searched for galaxies at a redshift of around 6.55 [8]. This survey was conducted on the 4-m Mayall Telescope at Kitt Peak. There was one spectroscopically confirmed Lyα emitter. Another survey using the Subaru telescope found one Lyα emitter at $z = 6.96$ [4]. ZEN, which stands for z equals 9, is a narrow J-band mission using the ISAAC on the VLT, located no galaxies at a redshift of 8.76. [12, 13]. Finally, Cuby et al. [1] did a followup narrow-band search, using the ISAAC at the VLT, with a larger field of view (hereafter referred to as the ISAAC ext). They also detected no galaxies.

PROPERTIES OF LYα EMITTERS

In equation (2), the only free parameter was the mass-to-"observed light" ratio, M_h/L_{band}. Therefore, we vary M_h/L_{band} to give a model that is consistent with observations. (See Fig. 1)

We find that the Subaru data at $z = 5.7$ and $z = 6.56$ are consistent with no evolution of properties of Lyα emitters or the IGM opacity. The evolution in the number density of Lyα emitters can be explained solely by the evolution of the mass function. In addition, the similarity of M_h/L_{band} across redshifts indicates that properties of Lyα emitters and the IGM opacity have not evolved very much between $z = 5.7$ and 7. The lack of detection at $z = 8.76$ is also consistent with no evolution, although it does not provide a significant constraint yet.

Our analysis so far has been relatively model-independent. We have extracted the only free parameter, M_h/L_{band}, from various narrow-band searches of Lyα emitters. Here, M_h/L_{band} only describes the light observed over the narrow band. To proceed further and understand physical properties of Lyα emitters better, however, we must relate M_h/L_{band} to the mass-to-"bolometric light" ratio, M_h/L_{bol}, taking into account stellar populations as well as differences in the band-widths.

In order to get the actual mass to light ratio, the spectra of a stellar population of galaxies was modeled and integrated first over all frequencies and then compared to the light that is observed in the narrow band. The fraction of Lyα photons that survived, α_{esc}, also needs to be taken into account. As a result, each data-set yields a constraint on $(M_h/L_{bol})\alpha_{esc}^{-1}$ as a function of assumed stellar populations.

When the duty cycle is less than unity, the constraint should be interpreted as $(M_h/L_{bol})(\alpha_{esc}\varepsilon^{1/\gamma})^{-1}$, where $\gamma \sim 2$ is a local slope of the cumulative luminosity function, $N(>L) \propto L^{-\gamma}$, to which the current data are sensitive.

We modeled four mass functions: Salpeter, Larson, Heavy, and a delta function at 300 solar masses, as well as three stellar metallicities: $Z = 0, 1/50 Z_\odot$, and 1 $Z_\odot$. The synthetic spectrum emerging from a galaxy with a given population of stars is the result of a variety of radiation processes: stellar blackbody, the Lyα line, free-free, free-bound, and two-photon emission. We use analytical formulae for these spectra given in section 2

TABLE 1. The mass (total halo mass) to light (bolometric luminosity) ratio times $1/(\alpha_{esc}\,\varepsilon^{1/\gamma})$.

Field	Redshift	$\frac{M_h}{L_{bol}}\frac{1}{\alpha_{esc}\,\varepsilon^{1/\gamma}}$ $(Z=0)$	$\frac{M_h}{L_{bol}}\frac{1}{\alpha_{esc}\,\varepsilon^{1/\gamma}}$ $(Z=1/50\,Z_\odot)$	$\frac{M_h}{L_{bol}}\frac{1}{\alpha_{esc}\,\varepsilon^{1/\gamma}}$ $(Z=1\,Z_\odot)$
Subaru	5.7	$28-38$	$19-26$	$12-17$
LALA	6.55	$\sim 32-34$	$\sim 21-23$	$\sim 13-15$
Subaru	6.56	$21-26$	$14-19$	$8.9-12$
Subaru	7.025	$\sim 28-30$	$\sim 19-21$	$\sim 12-14$
ZEN	8.76	$> 0.79-0.84$	$> 0.53-0.59$	$> 0.34-0.39$
ISAAC ext	8.76	$> 0.34-0.36$	$> 0.23-0.25$	$> 0.14-0.17$

of Fernandez & Komatsu [2], paired with a line profile of Lyα emission from Loeb & Rybicki [7], Santos et al. [9]. Now, calculating the mass-to-bolometric light ratio of galaxies is simple: multiply the mass-to-observed light ratio (M_h/L_{band}) by the ratio of observed to bolometric luminosity. We tabulate $(M_h/L_{bol})(\alpha_{esc}\varepsilon^{1/\gamma})^{-1}$ inferred from various narrow-band searches in Table 1 .

We conclude from these results that the Lyα emitters detected in these narrow-band surveys are either normal galaxy populations with $M_h/L_{bol} \sim 10$ and having a fair fraction of Lyα photons escape, $\alpha_{esc}\varepsilon^{1/\gamma} \sim 0.5-1$, or starburst galaxies with $M_h/L_{bol} \sim 0.1-1$ having a smaller fraction of the Lyα photons escape from the galaxies themselves *and* the surrounding IGM, $\alpha_{esc}\varepsilon^{1/\gamma} \sim 0.01-0.05$. Note that the degeneracy still allows for a possibility of having a significant survival fraction from these starburst populations, e.g., $\alpha_{esc} \sim 0.5$, if $\varepsilon^{1/\gamma} \sim 0.1$ (or $\varepsilon \sim 0.01$ and $\gamma \sim 2$). In order to further constrain the population of Lyα emitters, one can look at the equivalent width (EW) of the Lyman-α line. However, the science is complicated - for the EW depends on the metallicity and age of the starburst.

Having the Lyα line be diminished in flux by about an order of magnitude from a small value of α_{esc} is not a surprising effect. Both the IGM and galaxies themselves are expected to scatter or absorb Lyα photons efficiently. The physics of this problem is complex; however, our results are consistent with a depletion of the Lyα flux if indeed these Lyα emitters are starburst galaxies with $M_h/L_{bol} \sim 0.1-1$.

Is there any "anomaly"? Let us focus on the Subaru fields at $z=5.7$ and 6.56, as these are the most accurate data-sets. We observe nearly 20–30% decrease in $(M_h/L_{bol})(\alpha_{esc}\varepsilon^{1/\gamma})^{-1}$ from $z=5.7$ to $z=6.56$. Although subtle, if this is indeed a real effect, what would be the implication? One needs to have a larger α_{esc} – hence a smaller opacity for Lyα photons – at higher z, perhaps due to less dust content [6]. An alternative possibility is that M_h/L_{bol} was lower in the past, i.e., the Lyα emitters were intrinsically brighter at higher z, perhaps due to a more intense starburst. Such a burst would create a large HII bubble around the source, which also helps to increase α_{esc} by suppressing the IGM opacity.

CONCLUSIONS

The inferred mass-to-light ratios are consistent with no evolution in the properties of Lyα emitters or opacity in the IGM from $5.7 \le z \le 7$. Therefore, the current data of the luminosity functions do not provide evidence for the end of reionization. The data at $z=8.8$ do not yield a significant constraint yet.

These mass-to-light ratios suggest that the Lyα emitters discovered in the current surveys are either starburst galaxies with only a smaller fraction of Lyα photons escaped from galaxies themselves and the IGM, $\alpha_{esc}\varepsilon^{1/\gamma} \sim 0.01-0.05$, or normal populations with a fair fraction of Lyα photons escaped, $\alpha_{esc}\varepsilon^{1/\gamma} \sim 0.5-1$. The luminosity function alone cannot distinguish between these two possibilities. There is a subtle hint that $20-30\%$ more Lyα photons survived from $z=6.5$ than from $z=5.7$.

This method is a way to specify properties of Lyman alpha emitters, which are a group of objects that have mostly unknown characteristics. It can also be used to help design deep field searches by predicting how large the survey area must be to detect a certain number of Lyα emitters.

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