HIGH-n HYDROGEN RECOMBINATION LINES FROM THE FIRST GALAXIES

E. Rule1, A. Loeb2, and V. S. Strelnitski3

1 Johns Hopkins University & Maria Mitchell Observatory, 4 Vestal Street, Nantucket, MA 02554, USA
2 Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138, USA
3 Maria Mitchell Observatory, 4 Vestal Street, Nantucket, MA 02554, USA

Received 2013 August 5; accepted 2013 August 19; published 2013 September 5

ABSTRACT

We investigate the prospects of blind and targeted searches in the radio domain (10 MHz to 1 THz) for high-n hydrogen recombination lines from the first generation of galaxies, at \(z \lesssim 10\). The expected optically thin spontaneous \(\alpha\)-line luminosities are calculated as a function of the absolute AB magnitude of a galaxy at 1500 Å. For a blind search, semi-empirical luminosity functions are used to calculate the number of galaxies whose expected flux densities exceed an assumed detectability threshold. Plots of the minimum sky area, within which at least one detectable galaxy is expected at a given observing frequency, in the fiducial instantaneous passband of \(10^4\) km s\(^{-1}\), allow us to assess the blind search time necessary for detection by a given facility. We show that the chances for detection are the highest in the millimeter and submillimeter domains, but finding spontaneous emission in a blind search, especially from redshifts \(z \gg 1\), is a challenge even with powerful facilities, such as the Atacama Large Millimeter/Submillimeter Array and Square Kilometre Array. The probability of success is higher for a targeted search of lines with principal quantum number \(n \sim 10\) in Lyman-break galaxies amplified by gravitational lensing. Detection of more than one hydrogen line in such a galaxy will allow for line identification and a precise determination of the galaxy’s redshift.

Key words: galaxies: formation – H\(\Pi\) regions – masers

1. INTRODUCTION

Detection of spectral lines from the first generation of galaxies responsible for the reionization of the universe is one of the primary goals of observational cosmology (Loeb & Furlanetto 2012). Most of the galaxies currently known at redshifts \(z = 8-10\) were detected photometrically (Bouwens et al. 2011; Finkelstein et al. 2012), and have significant uncertainties in their redshift identification. More accurate determination of the redshift by spectroscopic identification would allow for probing the evolution of cosmological structure on small scales at early cosmic times and it would shed light on the sources for the reionization of hydrogen. The detection of Ly\(\alpha\) and other low-\(n\) Rydberg lines of hydrogen is challenging and was proven practical so far mainly at \(z \ll 7\) (Ouchi et al. 2010). Complementary information can be obtained from 21 cm surveys (Pritchard & Loeb 2012).

Here we investigate the possibility of detecting high-\(n\) hydrogen recombination lines from the large H\(\Pi\) regions expected around the hot, massive stars in the first generation of galaxies. Extragalactic hydrogen recombination radio lines in centimeter and millimeter domains have been detected in more than a dozen of starburst and Seifert galaxies (see chapter 3.5 in Gordon & Sorochenko 2002 for a review). The farthest galaxy with positive detections of radio recombination lines is Arp 220, at \(z = 0.018\), with flux densities up to \(\sim 100\) mJy in millimeter lines (Anantharamaiah et al. 2000). The typical width of the emission features in extragalactic recombination radio line spectra is \(\sim 100\) km s\(^{-1}\). These results were explained by spontaneous or amplified (maser) radiation from a multitude of H\(\Pi\) regions of various sizes, from \(\sim 0.1\) pc to a few parsecs.

Although the sensitivity of radio telescopes and interferometers is growing rapidly, and \(\mu\)Jy and even nJy thresholds of detectability are being discussed for the new and upcoming facilities, the jump from \(z \sim 0.02\) to \(z \sim 10\), corresponding to an increase of luminosity distance by three orders of magnitude (from \(\sim 10^2\) to \(\sim 10^5\) Mpc) is challenging. In Section 2, we describe our method of calculation. We derive a simple analytical expression relating the expected flux densities in H\(\alpha\) lines, spontaneously emitted from an optically thin medium, with the galaxy’s absolute AB magnitude at 1500 Å. Using the parameters of the monochromatic 1500 Å luminosity functions derived by Tacchella et al. (2013) for a discrete set of redshifts in the range \(z \lesssim 10\), we develop empirical equations providing the Schechter parameters for any \(z\) in this range. In Section 3, we present and discuss the results of the calculations. Using the numerical code described in Section 2, we find the number of galaxies whose flux density in at least one H\(\alpha\) line surpasses a given threshold of detectability at a given observing frequency, within a fiducial instantaneous passband. This allows us to consider the prospects of a blind search for these lines (Section 3.1). In Section 3.2, we show that, at present, the highest probability of detecting hydrogen recombination lines from galaxies with \(z \gtrsim 6-7\) is for Lyman-break galaxies amplified by gravitational lensing. In Section 3.3, we briefly consider several effects that may influence our estimates of the flux densities and show that probably none of them can change our predictions by more than an order of magnitude. Our conclusions are summarized in Section 4.

2. METHOD OF CALCULATION

Our goal is to estimate the expected flux densities in high-\(n\) hydrogen recombination lines from remote galaxies in the radio domain (from 10 MHz to 1 THz), in order to see whether a blind or targeted search for such lines is practical with existing or forthcoming facilities. Specifically, for a blind search, we want to determine the minimum sky area, \(\Omega_{\Delta\nu}(v_0)\), within which one can expect to find at least one galaxy satisfying the following three conditions: (1) its redshift \(z \lesssim 10\); (2) its spontaneous, optically thin radiation in at least one hydrogen recombination line falls within a given instantaneous passband \(\Delta\nu_0\) around the chosen observing frequency \(v_0\); and (3) the expected flux density of this radiation exceeds a certain threshold, \(f_{\text{th}}\).
We limit ourselves to the strongest, H\textalpha, lines, i.e., the lines due to \((n + 1) \rightarrow n\) transitions, where \(n\) is the principal quantum number.

The redshift at which the line has to be emitted in order for it to be red-shifted to the observed frequency \(v_\text{f}\) is:

\[
z_e (v_\text{f}, n) = \frac{v - v_\text{f}}{v_\text{f}} = \frac{c R_H}{v_\text{f}} \left[ \frac{1}{n^2} - \frac{1}{(n + 1)^2} \right] - 1,
\]

where \(v\) is the rest frequency of the transition and \(R_H = 1.0968 \times 10^5 \text{ cm}^{-1}\) is the Rydberg constant for hydrogen.

Differentiating Equation (1) gives:

\[
dz_e = -\frac{v}{v_\text{f}} \frac{dv_\text{f}}{v_\text{f}}.
\]

Integration over the passband,

\[
\Delta v_\text{f} = \frac{\Delta v_0}{c},
\]

gives the redshift interval corresponding to the width of the passband:

\[
|\Delta z_e| = \frac{v}{v_\text{f}} \left| \frac{1}{v_\text{f}} + 0.5 \frac{\Delta v_0}{v_\text{f}} - \frac{1}{v_\text{f} - 0.5 \Delta v_0} \right|
= \frac{v}{v_\text{f}} \frac{\Delta v_0}{v_\text{f}} = (z_e + 1) \frac{\Delta v_0}{c},
\]

where \(\Delta v_0\) is the passband in velocity units, and the last two equalities are asymptotically correct for \(\Delta v_0 \ll v_\text{f}\).

All our calculations were made with the fiducial value of \(\Delta v_0 = 10^5 \text{ km s}^{-1}\) (\(\Delta v_0/v_\text{f} = 0.033\)), for five values of \(f_{\text{H}\alpha}\): 0, 0.1, 1, 10, and 100 \(\mu\text{Jy}\). Setting the value of \(f_{\text{H}\alpha}\), we have the code loop over the grid values of \(v_\text{f}\). For each grid value, the code loops over a range of principal quantum numbers \((5 \leq n \leq 1000)\) to find for each H\textalpha line the values of \(z_e(v_\text{f}, n)\) and \(|\Delta z_e| (z_e)\), from Equations (1) and (4), respectively. Then the code loops over a grid of the absolute AB magnitudes of the galaxies at 1500 \(\AA\), \(M_{\text{AB}}(1500)\), to find the number of galaxies, within \(|\Delta z_e| (z_e)\), that produce at least one detectable H\textalpha line each. The total number of detectable galaxies, \(N_{\text{det}}(v_\text{f})\), determines the minimum search area \(\Omega_4 = 4\pi/\Omega_{\text{det}}(v_\text{f})\). The index “4” indicates that calculations were done for \(\Delta v_0 = 10^4 \text{ km s}^{-1}\).

The relation between \(M_{\text{AB}}(1500)\) of a galaxy and the expected flux density at the center of the H\textalpha line from this galaxy, \(f_{\text{H}\alpha}\), is found as follows.

The line flux density is:

\[
f_{\text{H}\alpha} = \frac{N_{\text{H}\alpha}}{\delta \nu_{\text{H}\alpha}} \frac{h \nu_{\text{H}\alpha} (z + 1)}{4 \pi d_L^2} = \epsilon_{\text{H}\alpha} V \frac{hc (z + 1)}{4 \pi d_L^2},
\]

where \(N_{\text{H}\alpha}\) is the rate of production of H\textalpha photons in the galaxy; \(\epsilon(\text{H}\alpha)\) is the photon emissivity \((\text{cm}^{-3} \text{ s}^{-1})\), \(V\) is the volume of the emitting gas; \(\nu_{\text{H}\alpha}\) is the rest-frame frequency of the line; \(\delta \nu_{\text{H}\alpha}\) and \(\delta \nu\) are the widths of the line in frequency and velocity units, respectively (the latter being the same for all the lines), \(d_L\) is the luminosity distance to the source, and the factor \((z + 1)\) accounts for the shrinkage of the observed frequency band as compared with the emitted frequency band. For a flat universe \((1 - \Omega_m - \Omega_\Lambda = 0)\), the luminosity distance is

\[
d_L = \frac{c}{H_0} (z + 1) \int_0^z \frac{dz'}{\Omega_m (z' + 1)^3 + \Omega_\Lambda}^{1/2},
\]

where \(H_0\) is the Hubble constant, and \(\Omega_m\) and \(\Omega_\Lambda\) are the total matter density and the dark energy density (in the units of critical density), respectively. The luminosity distance was calculated by numerical integration, adopting the WMAP 9 ACMD cosmological parameters: \(H_0 = 70 \text{ km s}^{-1}\), \(\Omega_m = 0.28\) and \(\Omega_\Lambda = 0.72\) (Hinshaw et al. 2012).

According to numerous calculations of hydrogen line populations in \(H^+\) regions (e.g., Hummer & Storey 1987), the ratio of \(\epsilon_{\text{H}\alpha}\) to the total recombination rate, \(\alpha, N^2\), is practically a constant for a broad range of electron densities. Using Hummer & Storey’s results for Menzel’s Case B (for which the total coefficient of photorecombination to the levels \(n \geq 2\), \(\alpha \approx 4 \times 10^{-11} \text{ cm}^3 \text{ s}^{-1}\), we derived the following empirical equation:

\[
\epsilon_{\text{H}\alpha} \approx 3.25 n^{-2.72} \alpha, N^2.
\]

This equation is based on the results for \(\alpha\)-transitions within the interval \(n = 3–29\), where it seems to be accurate within a few percent for any value of \(N_e\). With our goal of only rough estimates of expected fluxes, we used this equation for all the higher values of \(n\), up to \(n = 1000\).

The condition of ionization equilibrium requires

\[
\alpha, N^2 V \approx N_{\text{H}\alpha} \left(1 - f_{\text{esc}}^{\text{H}\alpha}\right),
\]

where \(N_{\text{H}\alpha}\) is the rate of production of ionizing photons in the galaxy and \(f_{\text{esc}}^{\text{H}\alpha}\) is the escape fraction of these photons. The connection between \(N_{\text{H}\alpha}\) and the luminosity of the galaxy at 1500 \(\AA\) can be obtained in two steps. First, the 1500 \(\AA\) luminosity is related to the star formation rate (SFR) through (Muñoz & Loeb 2011):

\[
\frac{\text{SFR}}{M_\odot \text{ yr}^{-1}} \approx \frac{L_{1500}}{2 \times 10^{28} \text{ erg s}^{-1} \text{ Hz}^{-1}}.
\]

Second, with some assumptions about the initial mass function and the metallicity of the stars, one can obtain a relation between the SFR and the production rate of ionizing photons. Based on Table 4 from Schaerer (2003), we can adopt for the first-generation low-metallicity stars:

\[
\frac{N_{\text{H}\alpha}}{10^{44} \text{ photon s}^{-1}} \approx \frac{\text{SFR}}{M_\odot \text{ yr}^{-1}}.
\]

The last two equations are combined to yield

\[
\frac{N_{\text{H}\alpha}}{10^{25} \text{ photon s}^{-1}} \approx 5 \times 10^{25} \frac{L_{1500}}{\text{erg s}^{-1} \text{ Hz}^{-1}}.
\]

From the standard definition of the absolute magnitude, \(M(v)\), and the definition of the observed monochromatic AB magnitude, \(m_{\text{AB}}(v)\),

\[
\log_{10} f_v = \frac{-m_{\text{AB}}(v) - 48.6}{2.5},
\]

where \(f_v\) is the observed flux density, one obtains the relation between the absolute AB magnitude of the source and its monochromatic luminosity:

\[
L_v = 4 \pi \left(3.086 \times 10^{19}\right)^2 f_v [M_{\text{AB}}(v)]
= 4.346 \times 10^{20} \times 10^{-0.4 m_{\text{AB}}(v)} \text{ erg s}^{-1} \text{ Hz}^{-1}.
\]
From Equations (5), (7), (8), (11), and (13), we finally get:

\[ f_{\text{H}α} \approx 1.2 \times 10^{-7} n^{-2.72} 10^{-0.4 M_{\text{AB}}^7 (z + 1)} \times \left( \frac{d_L}{10^8 \text{ Mpc}} \right)^{-2} \left( \frac{\delta v}{100 \text{ km s}^{-1}} \right)^{-1} (1 - f_{\text{esc}}^{912}) \text{ (µJy)}. \] (14)

The comoving number density of galaxies as a function of \( z \) and \( M_{\text{AB}} \) is found from the Schechter luminosity function (we drop the subindex AB):

\[ \phi(M, z) = (0.4 \ln 10) \phi_*(z) \times \left[ 10^{0.4[M(z) - M_*]} \right]^{1+\alpha(z)} \exp \left( -10^{0.4[M(z) - M_*]} \right). \] (15)

The values of the parameters \( \phi_*(z) \), \( M_*(z) \), and \( \alpha(z) \) are calculated using the empirical equations based on these parameters for 10 discrete values of \( z \) (0.3, 1, 2, ..., 8, 10) in the UV luminosity model of galaxies by Tacchella et al. (2013), which is in a good agreement with the observed statistics of galactic luminosities. The empirical equations were determined separately for \( 0 \leq z < 5 \) and \( 5 \leq z \leq 10 \):

\[ \phi_{3}^* \approx -0.08251 z^5 + 1.2092 z^4 - 6.5396 z^3 + 15.892 z^2 - 16.880 z + 8.0006 \quad (0 \leq z < 5), \] (16)

\[ \phi_{3}^* \approx 14.316 e^{-0.418 z} \quad (5 \leq z \leq 10); \] (17)

\[ M_* \approx -0.711 \ln z - 19.842 \quad (0 \leq z < 5), \] (18)

\[ M_* \approx 1.1683 \ln z - 22.501 \quad (5 \leq z \leq 10); \] (19)

\[ \alpha \approx -0.155 \ln z - 1.5239 \quad (0 \leq z < 5), \] (20)

\[ \alpha \approx -0.595 \ln z - 0.7358 \quad (5 \leq z \leq 10). \] (21)

Note that the first two equations give \( \phi_{3}^* \) in the units of \( 10^{-3} \text{ Mpc}^{-3} \text{mag}^{-1} \); the parameter \( \phi^* \) entering equation (15) is obtained from \( \phi_{3}^* \) by dividing by \( 10^3 \).

3. RESULTS AND DISCUSSION

3.1. Blind Search

From Equation (14), for the most luminous galaxies (\( M_{\text{AB}}^{7} \sim -22 \)) at \( z \sim 10 \) (\( dl \sim 10^3 \text{ Mpc} \)), assuming \( f_{\text{esc}}^{912} = 0 \), the expected flux densities in the \( n \sim 10 \) lines are \( \sim 1 \text{ µJy} \), and for such galaxies at \( z \lesssim 1 \) (\( dl \sim 10^3 \text{ Mpc} \)) the fluxes in the \( n \sim 10 \) lines are \( \sim 10^2 \text{ µJy} \). Modern radio astronomy is at the threshold of mastering the \( \text{µJy} \) level. However, the galaxies of \( M_{\text{AB}}^{7} \sim -22 \) must be very rare, especially at redshifts \( \gtrsim 10 \). To assess the prospect of detecting any galaxies in a blind search via their high- \( n \) hydrogen recombination lines we used the approach described in Section 2. We assumed that the width of all the lines is \( \Delta v = 100 \text{ km s}^{-1} \) and that \( f_{\text{esc}}^{912} = 0 \).

The results of the calculations are presented in Figures 1 and 2. Figure 1 shows the dependence of \( \Omega_4 \) on the observing frequency. The “No threshold” curve shows the total number of the star-forming galaxies that have any lines in the range of \( n \) we consider (\( 5 \leq n \leq 1000 \)), which would fall in the passband \( \Delta v_0 = 0.033 v_0 \) around an observing frequency \( v_0 \). The increase of the minimum search area with increasing detection threshold is understandable. The shape of individual curves, corresponding to various values of the detection threshold, can be explained by the combined effects of the dependence of \( f_{\text{H}α} \) on \( n \); the dependence of the luminosity function on the redshift; the decreasing interval between the adjacent lines with the increasing \( n \); and the limited range of the lines included in the calculations. For all the considered non-zero detection thresholds, the minimum search area decreases with increasing frequency, up to the highest radio frequency considered here, \( v_0 \approx 1 \text{ THz} \).

As illustrative examples, we consider the prospects of a blind search with the Actama Large Millimeter/Submillimeter Array (ALMA), the Square Kilometre Array (SKA), and the Low-Frequency Array (LOFAR).

When fully operational, ALMA will be capable of observing from 84 to 950 GHz. Let us consider, for instance, a search at 100 GHz (ALMA’s band 3). According to the ALMA sensitivity calculator, observations with a spectral resolution of 100 km s\(^{-1}\) and the maximum recoverable scale of 8.6 arcsec (the ALMA C32-6 configuration) will provide a detection threshold of \( \sim 2 \text{ µJy} \) in 1 hr of integration. From Figure 2, the minimum search area for this threshold at \( v_0 = 100 \text{ GHz} \) is \( \approx 20 \text{ arcmin}^2 \).
This area contains $\approx 1000$ elements of 8.6 arcsec scale. Thus, the total search time should be $\gtrsim 10^3$ hr.

The prospect of detection is similar for SKA. If a sensitivity of $\sim 10^4$ m$^2$ K$^{-1}$ is achieved for the planned highest frequency of 30 GHz, then, with the system’s noise temperature $\sim 10$ K, a detection threshold $10 \mu$Jy will be achieved in 1 hr of integration for a spectral resolution of $\sim 100$ km s$^{-1}$. According to Table 2, this threshold corresponds to a minimum search area $\sim 10^5$ arcmin$^2$, which is about three orders of magnitude larger than the expected instantaneous SKA field of view at this frequency. Thus, again, integration times $\gtrsim 10^3$ hr will be needed for a detection.

According to the LOFAR imaging capabilities and sensitivity Web Site, LOFAR’s sensitivity, calculated for a bandwidth of 3.66 MHz and 8 hr of integration, is $\approx 4$ mJy at the lowest frequency of 30 MHz and $\approx 1$ mJy at the highest frequency of 240 MHz. Recalculating for a 100 km s$^{-1}$ bandwidth and 1000 hr of integration (to compare with the cases of ALMA and SKA), gives the sensitivities of $\approx 7$ mJy and $\approx 0.6$ mJy, respectively. Addressing Figure 1, we find that, for both frequencies, the minimum search area is much greater than the whole celestial sphere, which makes the search unrealistic.

These pessimistic prospects of detecting an optically thin spontaneous emission in high-$n$ lines from far-away galaxies in a blind search are made worse by the fact that the number of detectable galaxies identified by Zheng et al. (2012). Its estimated redshifts may be detectable in hydrogen recombination lines from such galaxies either. Based on the analysis of maser saturation by Strelbitski et al. (1996), we estimate that possible maser amplification in any of the $n \sim 10$ lines is limited by factors $\approx 10$. So, even if masing does occur in some of these lines, it may improve the prospects of detection only slightly.

4. CONCLUSIONS

We studied the prospects of detecting high-$n$ hydrogen recombination lines from the first-generation galaxies at $z \lesssim 10$ with existing or forthcoming radio-astronomical facilities. A blind search for such lines seems to be challenging even with the best existing and planned facilities, such as ALMA, LOFAR, and SKA. However, some $z \gg 1$ galaxies with photometrically estimated redshifts may be detectable in $n \sim 10$ lines with facilities like ALMA, if they are amplified by gravitational lensing. The detection of radio recombination lines from such galaxies would allow for a precise determination of their redshifts.

E.R. was a Maria Mitchell Observatory REU intern while working on this project. He gratefully acknowledges the support by the NSF REU grant AST-0851892 and by the Nantucket Maria Mitchell Association. The work was also supported in part by NSF grant AST-0907890 and NASA grants NNX08AL43G and NNA09DBB30A (for A.L.). The authors thank the anonymous referee for the careful reading of the Letter and several valuable suggestions.

REFERENCES

Anantharamaiah, K. R., Viallefond, F., Mohan, N. R., Goss, W. M., & Zhao, J. H. 2000, ApJ, 537, 613

Bouwens, R. J., Illingworth, G. D., Oesch, P. A., et al. 2011, ApJ, 737, 90

Finkelstein, S. L., Papovich, C., Ryan, R. E., et al. 2012, ApJ, 758, 93

Gordon, M. A., & Sorochenko, R. L. 2002, Radio Recombination Lines (Astrophysics and Space Science Library, Vol. 282; Dordrecht: Kluwer)
Hinshaw, G., Larson, D., Komatsu, E., et al. 2012, arXiv:1212.5226
Hummer, D. J., & Storey, P. J. 1987, MNRAS, 224, 801
Loeb, A., & Furlanetto, S. R. 2012, The First Galaxies in the Universe (Princeton, NJ: Princeton Univ. Press)
Munoz, & Loeb, A. 2011, ApJ, 729, 99
Ouchi, M., Shimasaku, K., Furusawa, H., et al. 2010, ApJ, 723, 869
Pritchard, J. R., & Loeb, A. 2012, RPPh, 75, 086901
Schaefer, D. 2003, A&A, 397, 527
Strelnitski, V., Ponomarev, V., & Smith, H. 1996, ApJ, 470, 1118
Tacchella, S., Trenti, M., & Carollo, M. 2013, ApJL, 768, L37
Wood, K., & Loeb, A. 2000, ApJ, 545, 86
Zheng, W., Postman, M., Zitrin, A., et al. 2012, Natur, 489, 406