Constraining reionization with Lyman-alpha emitters and the CMB

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Illuminating the Dark Ages 2016, MPIA
CMB and the epoch of reionization

Loeb 2006

\[ z \approx 1100 \]

\[ z \approx 6 \]

cosmic dark ages

first stars and galaxies

CMB

reionization

today
CMB and the epoch of reionization

Loeb 2006

CMB
cosmic dark ages
first stars and galaxies
reionization
today

$z \approx 1100$
$z \approx 6$
CMB and the epoch of reionization

Loeb 2006

Thomson scattering

CMB

cosmic dark ages

first stars and galaxies

reionization

today

Loeb 2006

z ≈ 1100

z ≈ 6
CMB and the epoch of reionization

Loeb 2006

z ≈ 1100

Thomson scattering

z ≈ 6

first stars and galaxies

reionization

cosmic dark ages

today
CMB and the epoch of reionization

Loeb 2006

CMB

cosmic dark ages

first stars and galaxies

reionization

today

Loeb 2006

Thomson scattering

Lyman-alpha forest

QSO

z ≈ 1100

z ≈ 6

z ≈ 1000

z ≈ 0

time
CMB and the epoch of reionization

Loeb 2006

CMB

cosmic dark ages

first stars and galaxies

reionization

time

Thomson scattering

Lyman-alpha emitting galaxy

QSO

Lyman-alpha forest

z ≈ 1100

z ≈ 6

today

Figure 1. Spectra of $z \approx 6$ quasars analysed in this work that are in addition to those in the Fan et al. (2006) sample. ULAS J1319+0950 and ULAS J0148+0600 were observed with VLT/X-Shooter, while the remainder were observed with Keck/ESI (see Table 1). Approximate fluxing is based on published $z'$-band magnitudes. The spectra have been binned for display. Note that the Ly$\alpha$ forest flux for SDSS J2315−0023 appears depressed because the $y$-axis has been scaled to accommodate the strong Ly$\alpha$ emission line.

Error estimates do not include continuum errors, which are instead incorporated into the modelling (see Section 4). In order to avoid contamination from the quasar proximity region or from associated Ly$\beta$ or O$\ VI$ absorption, we generally restrict our measurements to the region between rest-frame wavelengths 1041 and 1176 Å. This also minimizes uncertainties in the continuum related to the blue wing of the Ly$\alpha$ emission line. For four of the six $z_{\text{em}}>5.9$ objects, however, we choose the maximum wavelength to lie just blueward of the apparent enhanced transmission in the proximity zone, as done by Fan et al. (2006). Exceptions to this are SDSS J0353+0104, which is a broad absorption line (BAL), and SDSS J2054−0005, for which edge of the region of enhanced flux is unclear. In these cases we use a maximum rest-frame wavelength of 1176 Å.
Probing the ionization & thermal state of the IGM

- Lyman-α emitters as a probe of reionization

Dijkstra 2014
Probing the ionization & thermal state of the IGM

- Lyman-α emitters as a probe of reionization

Dijkstra 2014
Probing the ionization & thermal state of the IGM

frequency diffusion of Lyman-α photons

- Lyman-α emitters:
- line usually redshifted with respect to systemic velocity
Probing the ionization & thermal state of the IGM

• Lyman-α emitters as a probe of reionization
Semi-numerical models of reionization

- semi-numerical models based on the ionizing photon budget, ionized if:
  ionizing photons - recombinations > number of hydrogen atoms

- excursion set approach:
  check for each point if there is any radius inside which the ionization condition is satisfied
  - no
  - not ionized
  - yes
  - ionized
Semi-numerical reionization in post-processing

- empirical assignment of ionizing luminosity to halos

-> get ionized regions in post-processing from simulations

Choudhury, EP, Haehnelt, Bolton 2015
hybrid technique combining large and small box

Choudhury, EP, Haehnelt, Bolton 2015
Iterative calibration of the photoionization rate

Overview of the main properties of our reionization models. Our default and late reionization models are shown in blue and red, respectively. In light of the close match with observational data, our model is evolutionary consistent down to $z=5$. All other quantities are calculated self-consistently. For the default model, $Q_M(\tau_{\rm eff})=0.086$ in the default model. The $Q_M(\tau_{\rm eff})$ of gas below an overdensity of 100. The lower right panel shows the globally averaged comoving emission rates of ionizing photons that our models imply, calibrated by fixing the evolution of the ionized mass fraction, and Appendix C for a detailed discussion. The black solid curves show predictions of the Planck result. The green squares in the lower middle panel show the optical depth due to Thomson scattering to the Planck 2013 and polarization data (Planck Collaboration XIII 2015 results (Planck Collaboration XVI 2014), but is fully consistent with the latest Planck result (Planck Collaboration XVI 2015). The green squares in the lower middle panel show the Planck 2013 and polarization data (Planck Collaboration XIII 2015 results (Planck Collaboration XVI 2014), but is fully consistent with the latest Planck result (Planck Collaboration XVI 2015).

We now examine the Ly$\alpha$ emitters and ionized regions obtained in our models. Observational constraints from Wyithe & Bolton (2011) are shown for reference. The lower left panel displays the mean-free path of ionizing photons at 1 Ryd measured sightlines is shown in Fig. 4 (Planck Collaboration XVI 2014). The upper middle panel compares the optical depth due to Thomson scattering to the Planck 2013 and polarization data (Planck Collaboration XIII 2015 results (Planck Collaboration XVI 2014), but is fully consistent with the latest Planck result (Planck Collaboration XVI 2015). The green squares in the lower middle panel show the Planck 2013 and polarization data (Planck Collaboration XIII 2015 results (Planck Collaboration XVI 2014), but is fully consistent with the latest Planck result (Planck Collaboration XVI 2015).
Iterative calibration of the photoionization rate

choose

reionization history

- In this model, the electron scattering optical depth is reduced to changes in the quantities of interest as shown in Fig. 4.
- At higher redshift, there are moderate differences due to a somewhat later reionization redshift in our small box (\(z>7\)). The green squares in the lower middle panel show the 2013 Planck constraints obtained from Planck temperature and polarization data (Planck Collaboration XIII 2015 results (Planck Collaboration XVI 2014), but is fully consistent with the latest observational constraints from Wyithe & Bolton (2011, hereafter W11) and Songaila & Cowie (2009)). The upper right panel shows the average hydrogen photoionization rate within ionized regions obtained in our models. Observational constraints from Wyithe & Bolton (2011, hereafter W11) are shown for reference. The lower left panel displays the mean-free path of ionizing photons at 1 Ryd measured in our default reionization model, the properties at \(z=0.72\) as opposed to \(z=0.066\) in the default model. The value of \(\tau_{el}\) in the late reionization model is therefore lower than that of the simulations in Pawlik, Schaye 2009, hereafter HM2012, UV-background model.

- The grey is shown a model, called the very late reionization model, where Ly \(_\alpha\) emitters and ionized regions are assumed to be strongly correlated (see Section 4.3). The lower middle panel compares the optical depth due to Thomson scattering to the Planck 2013 and 2015 results (Planck Collaboration XVI 2014, hereafter BB13) compared to that of the simulations in Pawlik, Schaye 2009, hereafter HM2012 UV-background model. Our models are calibrated by fixing the evolution of the ionized mass fraction, and Appendix C for a detailed discussion. The black solid curves show predictions of the clumping factor in the ionized regions. To allow a direct comparison to the clumping factor used in

- We now examine the Ly \(_\alpha\) damping wings redwards of the systemic redshift \(z=4.1\) for two different values of the photoionization rate within ionized regions obtained in our models. Observational constraints from Wyithe & Bolton (2011, hereafter W11) and Songaila & Cowie (2009) are shown for reference. Our models are

- The distribution of the transmitted fraction, \(e^\alpha\), at \(z=5\) in our late reionization model, the properties at \(z=9\) compared to those in Pawlik, Schaye 2009, hereafter HM2012 UV-background model.

- To form a sightline of length 100 pkpc, we first extract the 50 sightlines parallel to the box boundaries through the most massive dark matter haloes in the simulation box. (ii) Each of these sightlines is spliced with other randomly drawn sightlines in the box dark matter haloes in the simulation box. (i) we first extract method for calculating the absorption spectra: (i) we first extract absorption spectra. For this, we need to calculate sightlines from the simulation box. We use the following prescription on Ly \(_\alpha\) absorption spectra. For this, we need to calculate

- The distribution of the transmitted fraction, \(e^\alpha\), at \(z=5\) in our late reionization model, the properties at \(z=9\) compared to those in Pawlik, Schaye 2009, hereafter HM2012 UV-background model.
In this model, the electron scattering optical depth is reduced to identical to the default model. At higher redshift, there are moderate model, the values of the volume filling factor photoionization rate within ionized regions is weighed inversely by At high redshift, the photoionization rate is slightly higher as the difference is due to a somewhat later reionization redshift in our small box (difference in the ionized mass fraction, Appendix C for a detailed discussion). The black solid curves show predictions of the Planck result for the 2013 Planck constraints obtained from Planck temperature and polarization data (Planck Collaboration XIII 2015 results (Planck Collaboration XVI 2014), but is fully consistent with the latest observational constraints from Wyithe & Bolton (2011). The green squares in the lower middle panel show the 2013 Planck result obtained from Planck temperature and polarization data (Planck Collaboration XIII 2015 results (Planck Collaboration XVI 2014), but is fully consistent with the latest observational constraints from Wyithe & Bolton (2011). The green squares in the lower middle panel show the 2013 Planck result obtained from Planck temperature and polarization data (Planck Collaboration XIII 2015 results (Planck Collaboration XVI 2014), but is fully consistent with the latest observational constraints from Wyithe & Bolton (2011).
Iterative calibration of the photoionization rate

- Iterative calibration of the photoionization rate
- 
- In our late reionization model, the properties at $z_{\text{el}} = 0.072$ as opposed to $z_{\text{el}} = 0.066$ in the default model. The $\tau$ value of $Q_M$ is therefore lower than $Q_M$ in the default model. The individual sightlines is shown in Fig. 5. We find that $\tau_{\text{el}} = 0.086$ in the default model. The $\tau_{\text{el}}$ value of $Q_M$ remains $\pm 0.016$ (Planck Collaboration XIII 2014), hereafter 'minimal reionization model'. The $\tau_{\text{el}}$ in the late reionization model is also shown in the upper left panel, as well as the ionized volume fractions, $V_{\text{HI}}$, $V_{\text{HI}}(z_{\text{el}})$ chosen in our late reionization model is also shown in the upper left panel, as well as the ionized volume fractions, $V_{\text{HI}}$, $V_{\text{HI}}(z_{\text{el}})$. The Planck Collaboration XVI 2013 results (Planck Collaboration XVI 2014) are shown for reference. The lower left panel displays the mean-free path of ionizing photons at 1 Ryd measured to form a sightline of length 100 dark matter haloes in the simulation box. (ii) Each of these sightlines parallel to the box boundaries through the most massive dark matter haloes in the simulation box. (ii) Each of these sightlines from the simulation box. We use the following prescription on Ly$\alpha$ emitters and ionized regions are assumed to be strongly correlated (see Section 4.3). To make contact with the earlier work of Bolton & Haehnelt (2013), we therefore first discuss the effects of the self-shielding opacity arising from the IGM in our model, the electron scattering optical depth is reduced to changes in the quantities of interest as shown in Fig. 4. We should mention that we do not attempt to model the com-
Iterative calibration of the photoionization rate

\[ \frac{dQ_M}{dt} = \frac{\dot{n}_{\text{ion}}}{n_H} - \frac{Q_M}{t_{\text{rec}}} \]

Evolution of ionized fraction:

- \( Q_M \) filled symbols
- \( Q_V \) open symbols

Planck+WMAP 2013, 68%

- default
- late reionization
- very late reionization

Choudhury, EP, Haehnelt, Bolton 2015
Iterative calibration of the photoionization rate

![Graph showing the evolution of ionized fractions and the ionized fraction of HI over redshift with corresponding equations and data points.](Image)

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**Image Caption:**

The graph illustrates the iterative calibration of the photoionization rate with respect to redshift. It shows the evolution of ionized fractions $Q_V$ and $Q_M$ over redshift $z$, where $Q_M$ are filled symbols and $Q_V$ are open symbols. The $\lambda_{mp}$ scale is in $h^{-1}$ cMpc, and the $Q_M$ and $Q_V$ scales are in fractions. The equation for the evolution of the ionized fraction $Q_M$ is provided:

$$\frac{dQ_M}{dt} = \frac{\dot{n}_{ion}}{n_H} - \frac{Q_M}{t_{rec}}$$

The graph also includes data points and curves from various models such as WLB11, C11, BB13, and HM2012, with legend entries like default, late reionization, very late reionization, and HM2012. The left panel shows the mean-free path of ionizing photons at 1 Ryd measured by Planck+WMAP 2013, with Planck+WMAP 2013, 68% confidence level. The middle panel compares the optical depth due to Thomson scattering to the Planck 2013 and HM2012 predictions. The right panel displays the log of $\Gamma_{HI}$ as a function of redshift $z$.

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**Textual Description:**

The text describes the iterative process for calibrating the photoionization rate, which involves calculating the photoionization rate consistent with observed mean transmitted flux and the proximity effect in QSO reionization at the tail end of the hybrid volume. The baryonic density field is calculated from the large box. The text also mentions the use of numerical hydrodynamical simulations to determine the clumping factor in the ionized regions and the electron scattering optical depth.

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**Notes:**

1. The figure includes multiple graphs with different scales and axes.
2. The graph shows the evolution of ionized fraction $Q_M$ and $Q_V$ over redshift $z$.
3. The equation for the evolution of the ionized fraction $Q_M$ is provided.
4. The graph includes data points and curves from various models such as WLB11, C11, BB13, and HM2012.
5. The left panel shows the mean-free path of ionizing photons at 1 Ryd measured by Planck+WMAP 2013.
6. The middle panel compares the optical depth due to Thomson scattering to the Planck 2013 and HM2012 predictions.
7. The right panel displays the log of $\Gamma_{HI}$ as a function of redshift $z$.
Transmissivity for Lyman-α emission lines

Figure 6. Maps of the transmissivity for Lyman-α emission lines at different redshifts. The two upper rows show results for the default reionization model, while the two lower rows show results for the late reionization model. The intrinsic velocity shift is $v_{\text{int}} = 100 \text{ km s}^{-1}$, and the width of the Lyman-α profile is $\delta v = 88 \text{ km s}^{-1}$. These self-shielding simulations are implemented according to the SS-R model. The maps are coloured according to the transmissivity of the nearest emitter as seen in projection.

Choudhury, EP, Haehnelt, Bolton 2015
Transmissivity for Lyman-α emission lines

Figure 6. Maps of the transmissivity for Lyman-α emission lines at different redshifts. The two upper rows show results for the default reionization model, while the two lower rows show results for the late reionization model. The intrinsic velocity shift is \( v_{\text{int}} = 100 \text{ km s}^{-1} \), and the width of the Ly-α profile is \( 8 \text{ km s}^{-1} \). These self-shielding is implemented according to the SS-R model. The maps are coloured according to the transmissivity of the nearest emitter as seen in projection.

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Redshift evolution of the transmissivity

constant velocity shift

$\Delta v_{\text{int}} = 100 \, \text{km s}^{-1}$

transmissivity ratio

$T(z)/T(z = 5.5)$ default
$T(z)/T(z = 6.0)$ default
$T(z)/T(z = 5.5)$ late
$T(z)/T(z = 5.7)$ Konno et al. 2014
$T(z)/T(z = 5.7)$ Ouchi et al. 2010

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Intrinsic velocity shift vs redshift and luminosity

![Graph showing intrinsic velocity shift vs redshift and luminosity](Graph.png)

**Figure 8.**

*The relationship between the Lyα emission in the IGM and the absolute magnitude (M_{UV}). The discovery of a 340 km s⁻¹ velocity offset (Stark+15a) is consistent with the lack of evolution at z > 7. The presence of Lyα emission in this photometric sample is evidenced by the red symbols, which are more common in the luminous sample of galaxies described by Roberts-Borsani et al. (2016). The centroid of CIII] reveals that Lyα emission is redshifted from systemic velocities in most luminous systems. The existence of Lyα emission in two of the most luminous galaxies known at z = 7 suggests that these systems may have enough neutral gas at their systemic redshift to modulate the Lyα emission. The blue symbols corresponding to larger Lyα equivalent widths show a trend in luminosity-dependent evolution of LAEs at z > 7, with the open squares showing the relationship between M_{UV} and the Lyα equivalent width.*
Redshift evolution of the transmissivity

\[
\Delta v_{\text{int}} = \begin{cases} 
100 \text{ km s}^{-1} & \text{constant velocity shift} \\
100 \left( \frac{1+z}{7} \right)^{-3} \text{ km s}^{-1} & \text{evolving velocity shift}
\end{cases}
\]

\[ z \approx 6-8 \]

\[ \alpha \]

\[ \chi^2 \]

\[ \Delta \]

\[ \Delta v_{\text{int}} \]

\[ \frac{T(z)}{T(z = 5.5)} \]

\[ \frac{T(z)}{T(z = 6.0)} \]

\[ \frac{T(z)}{T(z = 5.5)} \text{ late} \]

\[ T(z)/T(z = 5.7) \text{ Konno et al. 2014} \]

\[ T(z)/T(z = 5.7) \text{ Ouchi et al. 2010} \]
Cumulative Lyman-α equivalent width distribution

evolving velocity shift

uncorrelated LAE positions
$\Delta v_{\text{int}} = 100[(1+z)/7]^{-3}$ km s$^{-1}$

strongly correlated LAE positions
$\Delta v_{\text{int}} = 100[(1+z)/7]^{-3}$ km s$^{-1}$

$P_z (\gtrsim \text{REW})$

$z = 5.0$
$z = 6.0$
$z = 7.0$
$z = 8.0$
$S11, z = 6$
$P14, z = 7$
$O12, z = 7$
$S14, z = 7$
$T14, z = 8$

default
late
intrinsic

default
very late
intrinsic

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Consistency with latest Planck constraints

- optical depth in Planck 2015/16 came down
- consistent with what we need for the Lyman-α emitters

\[ \tau_{el}(\langle z \rangle) \]

\( \tau_{el}(\langle z \rangle) \) such that the reionization is completed at \( z = 6 \), hereafter \( z < 6 \). The lower middle panel shows the average reionization model.

\[ \tau_{el}(\langle z \rangle) \]

\( \tau_{el}(\langle z \rangle) \) is the recombination rate coefficient. The mass-averaged ionization fraction, \( M_{H_2} \), is unchanged. We assume the same value as HM2012. We assume that helium is singly ionized in H. The small differences arising from the IGM in our models are relatively small.

\[ \tau_{el}(\langle z \rangle) \]

We now examine the Ly\( \alpha \) opacity arising from the IGM in our model. The distribution of the transmitted fraction, \( e^{\tau_{el}(\langle z \rangle)} \), is shown in the lower middle panel. The green squares in the lower middle panel show the predictions of the HM2012 UV-background model for reference. Our models are calibrated by fixing the evolution of the ionized mass fraction to be same as in Bolton & Haehnelt (2011, WB11).

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\[ \tau_{el}(\langle z \rangle) \]

We now examine the Ly\( \alpha \) opacity arising from the IGM in our model. The distribution of the transmitted fraction, \( e^{\tau_{el}(\langle z \rangle)} \), is shown in the lower middle panel. The green squares in the lower middle panel show the predictions of the HM2012 UV-background model for reference. Our models are calibrated by fixing the evolution of the ionized mass fraction to be same as in Bolton & Haehnelt (2011, WB11).
Summary

- **Lyman-α emitters:**
  - favour a late and not too extended reionization history (finishing at $z \sim 6$)
  - evolution of intrinsic velocity offsets may be important

- **CMB:**
  - Planck 2015/16 find lower optical depths \(\rightarrow\) late reionization in agreement with LAEs