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Authors: The user has provided a list of names: “Wen-Fei Liu, Yuan-Bo Xie, Zhi-E Liu, Jin Qin, Kang Jiao, Dong-Yao Zhao and Tong-Jie Zhang”

This appears to be author names for a scientific paper. The task is to translate from Simplified Chinese to English with the highest accuracy and academic tone. However, these are names, which typically don’ t need translation - they should be preserved as is.

Let me check the requirements: 1. Preserve ALL LaTeX commands and placeholders - not applicable here 2. Preserve ALL citation commands - not applicable 3. **PRESERVE ALL …paragraph wrapper tags EXACTLY** - not present in the input 4. Maintain academic tone and formal scientific writing style - names are already formal 5. Use precise technical terminology - not applicable 6. Preserve section structure and paragraph organization - not applicable 7. Translate all content completely - names are typically not translated

The input is just a list of names separated by commas and “and” . In academic contexts, Chinese names are usually written in Pinyin and kept as is. The format “Wen-Fei Liu” is already the standard English representation (given name first, family name last).

Since there are no tags, no LaTeX, no Chinese text to translate (the names are already in Pinyin), the output should be exactly the same as the input.

Wait, let me double-check: Are these names in Chinese characters that need to be transliterated? No, they are already in Pinyin format. So no translation is needed.

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But I need to check if there' s any hidden Chinese text. The names appear to be: - Liu Wenfei (刘文飞?) - Xie Yuanbo (谢元波?) - Liu Zhie (刘智娥?) - Qin Jin (秦晋?) - Jiao Kang (焦康?) - Zhao Dongyao (赵东耀?) - Zhang Tongjie (张同杰?)

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The user instruction says "Translate from

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Abstract

The user wants me to translate a Chinese academic text to English. Let me analyze the requirements:

1. **CRITICAL REQUIREMENTS**:
   - Preserve ALL LaTeX commands and placeholders exactly
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4. **Glossary**:
   - 机器学习 => machine learning
   - 深度学习 => deep learning

Now let me look at the input text. Wait, the user provided an English text, not Chinese. Let me re-read the prompt.

The user says: "We present constraints on the baryonic matter density parameter, Ωb, within the framework of the ΛCDM model. Our analysis utilizes observational data on the effective optical depth from high-redshift quasars. To parameterize the photoionization rate Γ−12, we employ a Bézier polynomial. Additionally, we approximate the Hubble parameter at high redshifts as km

s−1 Mpc−1. Confidence regions are obtained with h = 0.701 ± 0.013 and Ωm = 0.315, optimized by the Planck mission. The best-fit values are and , corresponding to an old data set and a new data set, respectively. We test the non-parametric form of Γ−12, obtaining . These results are consistent with the findings of Planck at the

Full Text

Preamble

Constraints on Baryon Density from the Effective Optical Depth of High-redshift Quasars

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Received 2024 November 18; revised 2025 January 19; accepted 2025 January 29; published 2025 February 21

Abstract

We present constraints on the baryonic matter density parameter, Ωb, within the framework of the ΛCDM model. Our analysis utilizes observational data on the effective optical depth from high-redshift quasars. To parameterize the photoionization rate Γ_{12}, we employ a Bézier polynomial. Additionally, we approximate the Hubble parameter at high redshifts as km s^{-1} Mpc^{-1}. Confidence regions are obtained with h = 0.701 ± 0.013 and Ωm = 0.315, optimized by the Planck mission.

The best-fit values are , corresponding to an old data set and a new data set, respectively. We test the non-parametric form of Γ_{12}, obtaining . These results are consistent with the findings of Planck at the 1σ confidence level. Our findings underscore the effectiveness of quasar data sets in constraining Ωb, eliminating the need for independent photoionization rate data. This approach provides detailed cosmic information about baryon density and the photoionization history of the intergalactic medium.

Key words: cosmology: observations -(cosmology:) cosmological parameters -cosmology: theory

1. Introduction

Quasars are among the most distant celestial objects observable as luminous sources, often at very high redshifts, with some approaching the epoch of reionization. This epoch occurred when the first generation of stars and quasars ionized the neutral intergalactic medium (IGM) (Holt & Smith 1999). The growing number of observations of high-redshift quasars has provided valuable measurements, establishing them as an effective probe for studying the early universe.

Keck and VLT spectroscopy of high-redshift quasars (Becker et al. 2001; Pentericci et al. 2002) revealed the first observation of a complete Gunn–Peterson trough in the spectrum of the z = 6.28 quasar SDSS 1030+0524. Becker et al. (2015) discovered an exceptionally long and dark Lyα trough that extends to high redshifts, representing the longest one found to date below a redshift of 6. Djorgovski et al. (2001) observed a particularly dark region of length approximately 5 Mpc at z 5.4 along the line of sight to the z 5.8 quasar SDSS 1044-0125. Observations by Fan et al. (2001), Becker et al. (2001), and Pentericci et al. (2002) demonstrated that the Lyα absorption due to neutral hydrogen in the IGM increases dramatically toward high redshifts.

One of the primary goals of cosmology is to constrain cosmological parameters using various observational quantities that depend on redshift. In this paper, we utilize measurements of the effective optical depth obtained from spectroscopic observations of high-redshift quasars, spanning a redshift range of z = 4.8–6.2, to constrain the baryon density parameter, Ωb. Some of these data sets have previously been employed to investigate the evolution of the ionizing background and the epoch of reionization (Fan et al. 2002, 2006). However, this study represents the first application of these data sets to constrain Ωb, a crucial cosmological parameter commonly determined through Cosmic Microwave Background (CMB) or Baryon Acoustic Oscillation (BAO) measurements from galaxy clustering. While these traditional methods are applicable at very high redshifts and relatively low redshift epochs, respectively, our work provides an important complement by utilizing high-redshift quasars to derive constraints on Ωb within the redshift range between the CMB and galaxies.

In Section 2, we present the observational data. The derivations of the effective optical depth and the constraint methods are introduced in Section 3. Finally, we discuss and conclude in Section 4.

2. Observational Data

In this work, we selected the effective optical depth data for Lyα from Fan et al. (2006) and the up-to-date sample from Bosman et al. (2022) to process cosmological constraints. For the spectra in Fan et al. (2006), 12 were obtained using the Keck ESI instrument, while the remaining spectra were observed using the MMT Red Channel and Kitt Peak 4 m MARS spectrographs. The data used in this study have a spectral resolution of approximately R 3000–6000, depending on seeing conditions. They binned all the Keck ESI spectra to a resolution of R = 2600. Although the signal-to-noise ratios (S/Ns) of these spectra vary by a factor of approximately 7, they obtained sufficiently long observations for all quasars at redshifts greater than 6.1 to ensure accurate measurement of complete Gunn–Peterson troughs. The nonuniform S/N among the lower redshift quasars does not significantly affect the analysis, as uncertainties in the average transmission are primarily influenced by large sample variance (Fan et al. 2006).

The data set used by Bosman et al. (2022) includes 30 quasar spectra at $z \geq 5.8$ from the XQR-30 program (1103.A-0817(A)), 26 archival spectra obtained with the X-Shooter spectrograph with equal SNR > 10 per 10 km s^{-1} pixel, and 16 archival spectra of quasars with $z \geq 5.7$ obtained with the ESI instrument on the Keck Telescope. All XQR-30 spectra have signal-to-noise ratios greater than 20 per 10 km s^{-1} pixel within the wavelength range of 1165 Å–1170 Å. The X-Shooter resolution is approximately 34 km s^{-1} in the visible range (5500 Å–10200 Å) and approximately 37 km s^{-1} in the infrared range (10200 Å–24800 Å). However, due to better-than-average seeing conditions during observations, the effective resolution is slightly higher. The ESI instrument has a lower spectral resolution of approximately 60 km s^{-1} and its wavelength coverage is limited to the optical range up to $\lambda < 10500$ Å. Figure 1 [Figure 1: see original paper] illustrates the distribution of SNRs for quasars obtained from the XQR-30, X-Shooter, and ESI data sets, clearly demonstrating that the XQR-30 data set generally exhibits higher SNR values. All quasar samples were divided into 14 bins, and the mean Lyα transmission was obtained for each bin.

In this study, we utilize the data from both Fan et al. (2006) and Bosman et al. (2022) to constrain the value of Ωb. Our analysis yields similar results that are in agreement with the findings of Planck Collaboration et al. (2020) within the 1σ confidence region.

3. Methodology

The effective optical depth is derived with the consideration that the IGM is inhomogeneous. This assumption is reasonable because the actual distribution of the IGM in the universe is complex and inhomogeneous, which necessarily affects observations. Another consideration in the derivation of theoretical effective optical depth is the approximation of the Hubble parameter at high redshifts. When z   1, the Hubble parameter H(z) can be approximated as km s^{-1} Mpc^{-1}. This approximation is advantageous because the observational data are all from quasars at very high redshifts (z = 4.8   6.2), some of which even approach the reionization epoch. We provide detailed derivations for the effective optical depth below.

3.1. Effective Optical Depth for Lyα

Assuming approximate thermal equilibrium between photoionization heating by the UV background and adiabatic cooling due to Hubble expansion (Hernquist et al. 1996; Hui & Gnedin 1997), the optical depth for Lyα and Lyman-β absorption lines, also known as the Gunn–Peterson optical depth, depends on the local density of the IGM. Therefore, the non-uniformity of the IGM must be taken into account. The fractional density of the IGM is defined as Δ / $\langle\ \rangle$ δ + 1 (where δ, the density contrast, is the departure of the local density from the mean density in units of the mean density). For a region of IGM with density Δ, the effective optical depth can be written as (Fan et al. 2002):

$$\tau_\alpha(\Delta) = \frac{\tau_0 \Omega_b h^2}{\Gamma_{-12}(z)} \frac{H_0}{H(z)} \Delta^2 \alpha(T)$$

where Ωb is the baryon density, Γ(z) is the photoionization rate, and α(T) is the recombination coefficient at temperature T (Abel et al. 1997). The dependence on Δ^2 comes from τ n_{HI} (Gunn & Peterson 1965), which is proportional to n_H^2 (Hernquist et al. 1996), and proportional to Δ^2 for a highly ionized IGM (Fan et al. 2002). The temperature of the IGM is determined by photoionization-recombination equilibrium, which leads to a power-law relation between temperature and density in the form of T = $T_0\Delta$^(γ−1), with T_0 1-2 × 10^4 K, and γ ranging from −1 to 0 (Hui & Gnedin 1997).

The optical depth for Lyα can be expressed as:

$$\tau_\alpha(\Delta) = \tau_1 \frac{\Omega_b h^2}{\Gamma_{-12}(z)} \frac{H_0}{H(z)} \Delta^2 T(z)^{-0.7}$$

where $\Gamma_{\ 12}$(z) is the photoionization rate in units of 10^{-12} s^{-1}, whose data matching the redshifts of samplers can be obtained from (Fan et al. 2002, 2006). The numerical constant τ_0 is determined below. T(z) is the temperature in units of 10^4 K, which will be discussed in Section 3.3.

At high redshift and km s^{-1} Mpc^{-1}, Equation (2) can be rewritten as:

$$\tau_\alpha(\Delta) = \tau_1 \frac{\Omega_b h^2}{\Gamma_{-12}(z)} \frac{1}{(1+z)^{3/2}} \Delta^2 T(z)^{-0.7}$$

where the numerical constant $\tau_1 = \tau_0/(3.24 \times 10^{-18})$ (in CGS unit system). We follow McDonald & Miralda-Escudé (2001) and set $\tau_1 = 0.664$, corresponding to $\tau_0 = 2.15 \times 10^{-18}$. Equation (3) is appropriate for all Lyman series lines, with different values of the proportionality constant (Fan et al. 2006).

The observed transmitted flux ratio T is averaged over the entire IGM density distribution (Fan et al. 2002):

$$\langle T\rangle = \int_0^\infty d\Delta\, p(\Delta)\exp[-\tau_\alpha(\Delta)]$$

This equation assumes that the universe is fully ionized. However, several recent studies, for example Kulkarni et al. (2019), have pointed out that this assumption may not hold true at z > 5.5. If the findings of Kulkarni et al. (2019) are accurate, the optical depth will be larger. In order to balance Equation (3), a larger value of Ωb is required. While we recognize that the assumption of full ionization may not be entirely valid in the redshift range z = 4.8-6.2, the IGM is predominantly ionized in this range, meaning that the assumption of full ionization remains approximately valid. Furthermore, the impact on the constraints of Ωb falls within the acceptable error margins of the parameter limits. To simplify the analysis and maintain consistency with previous studies, we continue to assume a fully ionized universe. It is important to note that our analysis is based on observational data, which generally support ionization in this redshift range, as demonstrated by Fan et al. (2002, 2006). However, future research may benefit from incorporating models with partial ionization, particularly at higher redshifts.

The distribution function of the IGM density, denoted as p(Δ), is a function of the volume-weighted density distribution (Miralda-Escudé et al. 2000):

$$p(\Delta) = A\exp\left[-\frac{(\Delta^{-2/3}-C_0)^2}{2(2\delta_0/3)^2}\right]\Delta^{-\beta}$$

The parameter $\delta_0 = 7.61/(1 + z)$, where z is the redshift, and the constants β, C_0, and A are numerical values listed in Table 1 of Miralda-Escudé et al. (2000) for various redshifts. These constants are obtained from numerical simulations, which align well with the observational results of the Lya forest transmitted flux (Rauch et al. 1997; Miralda-Escudé et al. 2000).

The definition of effective optical depth is τ_{eff} -ln T . Combining Equations (3), (4), (5) and (6), one can obtain the final equation for calculating the Lyα theoretical effective optical depth for inhomogeneous IGM with the high-redshift approximation of the Hubble parameter.

3.2. Parameterization of the Photoionization Rate Γ_{12}

In this work, we employ a Bézier fit to describe the evolution of Γ_{12} with redshift. The parameterization is given by:

$$\Gamma_{-12}(z) = \sum_{d=0}^{n} a_d \binom{n}{d}\left(\frac{z_m - z}{z_m}\right)^{n-d}\left(\frac{z}{z_m}\right)^d$$

where z_m is the maximum redshift in the quasar data, and a_d are the coefficients. This method, first introduced by (Amati et al. 2019), has been previously used to reconstruct Hubble data. We set n = 2 to balance the trade-off between the flexibility of the parameterization curve, determined by the number of coefficients a_d, and the precision of the fitting results, which is limited by the number of available data points. This parameterization takes advantage of the flexibility of Bézier curves compared with other curves like polynomials. The flexibility of Bézier curves is more advantageous for parametric constraints than other curves, such as polynomials.

3.3. Thermal History Parameters

We refer to Figure 2 in McQuinn & Upton Sanderbeck (2015) to establish a reasonable form for T(z) = T_0(z)Δ^(γ(z)−1). Figure 2 displays the thermal history for different densities ranging from 1 to 10. It is evident that within our region of interest z (4.8-6.2), the form of T(z) will have a significant impact on the optical depth τ_α(Δ). The curve depicted in Figure 2 of McQuinn & Upton Sanderbeck (2015) can be well approximated by the following two quintic polynomials.

3.4. Fitting Methods

Considering that the data are independently and identically distributed as Gaussian, we have a likelihood form as follows:

$$\ln \mathcal{L} = -\frac{1}{2}\sum_i \left[\frac{(\tau_{\rm eff}^{\rm th}(z_i) - \tau_{\rm eff}^{\rm obs}(z_i))^2}{\sigma_{\rm obs}^2(z_i) + \sigma_{\rm int}^2} + \ln(2\pi(\sigma_{\rm obs}^2(z_i) + \sigma_{\rm int}^2)) \right]$$

where τ*{eff}^{th}(z_i) is the predicted value of effective optical depth,* τ{eff}^{obs}(z_i) is the corresponding observational data, and σ*{int} is the global intrinsic dispersion.* σ{obs}(z_i) is the error in effective optical depth data. In this paper, we set Ω_m = 0.315 and h = 0.701 ± 0.101 (Planck Collaboration et al. 2020). a_0, a_1, a_2 are three parameters related to Γ_{12}.

To calculate the posterior distribution of the model parameters, we employed the Affine Invariant Markov Chain Monte Carlo (MCMC) ensemble sampler, emcee (Foreman-Mackey et al. 2013), implemented in Python. This method allowed us to survey the posterior distribution in the parameter space and maximize the likelihood function. The resulting contour plots were generated using the corner module (Foreman-Mackey 2016).

4. Discussion and Conclusion

The constraining results for the first data set from Fan et al. (2006) are shown in Figure 3 [Figure 3: see original paper]. Since the data are concentrated in the high-redshift range, the parameters a_0 and a_1 corresponding to the low redshift part of the curve cannot be well constrained. However, a_2, especially the most important parameter—the baryon density—has been well constrained.

The value of the baryon density is consistent with the results of Planck within a 1σ confidence interval. The 1σ confidence region is narrow, indicating high precision in our test results. Additionally, the left panel of Figure 5 [Figure 5: see original paper] shows the Lyα data and its theoretical values with the constrained parameters, while Figure 6 [Figure 6: see original paper] displays the reconstructed shape of Γ_{12}(z). We observe that the photoionization rate decreases with redshift, indicating the presence of abundant neutral hydrogen during the early stages of the universe.

For the second data set from Bosman et al. (2022), the constraining results are shown in Figure 4 [Figure 4: see original paper]. We obtain a slightly larger value of Ωb compared to that from Fan et al. (2006). Those results for Ωb are in good agreement with Planck Collaboration et al. (2020) within the 1σ confidence region. The right panel of Figure 5 [Figure 5: see original paper] shows the fitting results. Figure 6 [Figure 6: see original paper] shows the reconstructed ionization rate. It is clear that the results from the two data sets are similar at high redshift but exhibit larger dispersion at lower redshift. This is expected as we are using high-redshift data.

We also tested the robustness of the parameterization of Γ_{12} using a 4-parameter Bézier polynomial and a 5-parameter Bézier polynomial. The test results are shown in Figures 7 [Figure 7: see original paper] and 8 [Figure 8: see original paper], respectively. Compared to the 3-parameter case, the 4- and 5-parameter Bézier polynomials yield larger values of Ωb, respectively, which however remain consistent with the Planck results within 1σ.

A higher baryon fraction would lead to an increased number of electrons available for scattering photons, thereby augmenting the electron scattering optical depth. Furthermore, a greater baryon fraction implies a larger pool of baryons ready for star and galaxy formation, which could potentially stimulate galaxy formation and evolution at higher redshifts. The elevated baryon fraction can also influence feedback processes within galaxies. Feedback mechanisms, such as supernovae explosions and active galactic nuclei, control the growth of galaxies by infusing energy and momentum into the surrounding gas. With a higher baryon fraction, these feedback processes could become more efficient, potentially impacting the gas dynamics, star formation rates, and overall galaxy properties at higher redshifts. This could provide a more direct explanation for recent observations made by the James Webb Space Telescope (JWST) of more massive galaxies at these redshifts than previously anticipated (Labbé et al. 2023). Another possible reason for the larger Ωb value might be the relatively limited amount of data. However, this result still includes Planck's results within the 1σ region. Therefore, we must admit that the slight increase in Ωb is not sufficient to explain the abundance of bright galaxies at an early age. The parameterization form has a mild effect on the final results.

The constraining power on Ωb originates from redshift dependence. Equation (2) demonstrates the degeneracy between Γ_{12} and Ωb at a specific redshift. However, by combining data from different redshifts, we can break this degeneracy and place a strong constraint on Ωb. In such a case, Ωb would affect the amplitude of the τ_{eff} curve, while Γ 12 would influence both the amplitude and shape of the curve. Therefore, we test the non-parametric form of Γ 12(z). We use 15 parameters g_i ranging from i = 0 to 14, each representing Γ 12 at a specific redshift in the data. Because the data lie in the high-redshift range, we assume these parameters have a flat prior of (0 0.5). The test results are shown in Figure 6 [Figure 6: see original paper], and the corner plot for g_i is displayed in Figure 9 [Figure 9: see original paper]. From the plots, we can see that the baryon density parameter is well constrained: . The constraining power remains strong even with the non-parametric form of Γ 12.

Another important factor that could dramatically influence the results is the distribution function of the intergalactic medium' s density, which is shaped by Equation (5). We examined the influence of the four parameters on τ*{eff} and displayed the results in Figure 10 [Figure 10: see original paper]. It is evident that variations in these four parameters significantly affect* τ{eff}. Therefore, the robustness of our results partially depends on the accurate and comprehensive understanding of the IGM properties, especially the density distribution of the IGM.

In conclusion, this study represents the first effort to use two sets of effective optical depth data obtained from high-redshift quasars to constrain the cosmological parameter Ωb. We found that incorporating photoionization rate data is not crucial, as the parameterization of Γ 12 proves effective when ample data are available. Despite the limited data set, our analysis yielded highly precise results with minimal uncertainties, showing good consistency with Planck Collaboration et al. (2020). Our work is valid for high-redshift $z \geq 4.5$. A high precision of thermal history and the correct shape of the density distribution are crucial for constraining Ωb. Future research will aim to refine the constraints on Ωb by combining these findings with data from low-redshift celestial objects such as supernovae, the Hubble parameter, and BAO. This integrated approach promises to further enhance our understanding of Ωb.

Acknowledgments

We are grateful for the insightful and useful comments of the referee that greatly helped us improve our manuscript. T.J.Z. (张同杰) dedicates this paper to the memory of his mother, Yu-Zhen Han (韩玉珍), who passed away 4 yr ago (2020 August 26). This work was supported by the National SKA Program of China (2022SKA0110202) and China Manned Space Program through its Space Application System.

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