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Patchy intergalactic He II absorption in HE 2347−4342*

The possible discovery of the epoch of He-reionization

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Abstract. We report on observations of redshifted He II 303.8 Å absorption in the high-redshift QSO HE 2347−4342 (z = 2.885, V = 16.1) with the Goddard High Resolution Spectrograph on board HST in its low resolution mode ($\triangle\lambda$ = 0.7 Å). With f_λ = 3.6 10^{-15} erg cm^{-2} s^{-1} Å^{-1} at the expected position of He II 304 Å absorption it is the most UV-bright high redshift QSO discovered so far.

We show that the He II opacity as a function of redshift is patchy showing spectral regions with low He II opacity ("voids") and regions with high He II opacity (blacked-out "troughs") and no detectable flux. Combination with high-resolution optical spectra of the Lyα forest using CASPEC at the 3.6 m telescope shows that the voids can be explained either exclusively by Lyα forest cloud absorption with a moderate $N_{\rm He\,ii}/N_{\rm H\,i}$ ratio $\eta \leq$ 100 and turbulent line broadening or by a combination of Lyα forest with $\eta = 45$ and thermal broadening plus a diffuse medium with $\tau_{\rm GP}^{\rm He\,ii} \approx 0.3$. Since the latter is a minimum assumption for the Lyα forest, a strict upper limit to a diffuse medium is $\Omega_{\rm diff} < 0.02\ {\rm h}_{50}^{-1.5}$ at z = 2.8.

In the troughs in addition to the Lyα forest opacity a continuous He II 304 Å opacity $\tau = 4.8^{+\infty}_{-2}$ is required. In case of photoionization, the troughs would require a diffuse component with a density close to $\Omega \simeq 0.077\,(\eta/45)^{-0.5}\ {\rm h}_{50}^{-1.5}$, i.e. all baryons in the universe, which is inconsistent, however, with the observed absence of such a component in the voids. A tentative interpretation is that we observe the epoch of partial He II reionization of the universe with patches not yet reionized. In that case a diffuse component with $\Omega_{\rm diff} \geq 1.3\ 10^{-4}\ {\rm h}_{50}^{-1}$ would be sufficient to explain the "trough" opacity. The size of the 1163–1172 Å trough is $\sim$ 6 ${\rm h}_{50}^{-1}$ Mpc or $\sim$ 2300 km s^{-1}, respectively.

We also discuss partially resolved He II absorption of a high-ionization associated absorption system. Despite its high luminosity HE 2347−4342 does not show a He II proximity effect. A possible reason is that the strong associated system shields the He II ionizing continuum.

Key words: quasars: individual: HE 2347−4342 – quasars: absorption lines – cosmology: observations

1. Introduction

A longstanding goal of observational cosmology has been the detection of a diffuse intergalactic medium (IGM), suspected to contain a major fraction of the baryons of the universe produced in the big-bang, by means of the Gunn-Peterson (1965) effect. The test using H I Lyα has been negative so far (e.g. Steidel & Sargent 1987; Giallongo et al. 1992, 1994). The conclusion has been that the IGM is highly ionized and/or contains a much lower fraction of the baryons of the universe than originally expected. Recent hydrodynamical models of structure formation indeed predict that the fragmentation of baryons is nearly complete and that a diffuse IGM is suppressed by two orders of magnitude (Miralda-Escudé et al. 1996; Meiksin 1997).

With the launch of the Hubble Space Telescope it was hoped to detect a highly ionized diffuse IGM via the He II Lyα (303.8 Å) line, which was predicted to be much more sensitive than H I Lyα.

The observation of absorption on the blue side of the He II 304 Å line in high-redshift QSOs has been pioneered by Jakobsen et al. (1994) who observed a completely absorbed spectrum (τ = $3.2^{+\infty}_{-1.1}$) on the blue side of the redshifted He II line in Q 0302−003 (z = 3.29). He II absorption in a second QSO, PKS 1935−692 (z = 3.18), was discovered with HST by Tytler (1995), with a similar result (cf. Jakobsen 1996),

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while Davidsen et al. (1996) observed a lower He II opacity (τ = 1.00 ± 0.07 at $\bar{z}$ = 2.4) toward HS 1700+6416 (z = 2.72) with HUT/ASTRO-2.

Due to their low spectral resolution, all these observations did not allow to distinguish between a He II 304 Å forest and absorption by a diffuse medium. By means of model calculations using high resolution optical H I Lyα forest spectra, both Songaila et al. (1995) for Q 0302−003 and Davidsen et al. (1996) for HS 1700+6416 demonstrated that the He II opacity could be explained by the Lyα forest alone with $N_{\mathrm{He\,ii}}/N_{\mathrm{H\,i}} \simeq$ 80, a value roughly consistent with photoionization calculations using predicted metagalactic radiation fields due to QSOs with absorption by intergalactic matter taken into account (Meiksin & Madau 1993; Giroux et al. 1995; Haardt & Madau 1996). On the other hand, recent reobservations of Q 0302−003 with the GHRS on board of HST by Hogan et al. (1997) seem to indicate that a diffuse component with $\Omega_{\mathrm{diff}} \simeq 0.01$ (h/0.7)$^{-1.5}$ is required in order to explain the He II opacity in the well-known "void" (cf. Dobrzycki & Bechthold 1991) in the Lyα forest of Q 0302−003. All the HST observations of the intergalactic He II opacity obtained so far suffered from the faintness ($V > 18$) of the QSOs. The difficulty in finding more suitable targets is best demonstrated by the fact that the FOC surveys for unabsorbed $z > 3$ QSOs by Jakobsen et al. and Tytler et al. detected only 2 moderate opacity lines of sight in more than 110 observed QSOs (cf. Jakobsen 1996). In this paper we report on the discovery of the extremely bright (V = 16.1), z = 2.885 QSO HE 2347−4342 within the Hamburg/ESO survey for bright QSOs and on successful observations of He II 304 Å absorption with the GHRS onboard the Hubble Space Telescope in its low resolution mode. The combination of partially resolved He II absorption with high resolution optical spectra taken with CASPEC at the ESO 3.6 m telescope allows to constrain the $N_{\mathrm{He\,ii}}/N_{\mathrm{H\,i}}$ ratio in Lyα forest clouds and to quantify the contribution of a diffuse component to the He II absorption.

2. Observations

2.1. Discovery and IUE observations

The bright high redshift QSO HE 2347−4342 was discovered as part of the Hamburg/ESO Survey for bright QSOs a wide-angle survey based on objective-prism plates taken with the ESO 1 m Schmidt telescope. The plates are digitized in Hamburg and automatically searched for QSO candidates which are subsequently observed spectroscopically with ESO telescopes (Reimers 1990; Wisotzki et al. 1996; Reimers et al. 1996). HE 2347−4342 was confirmed as an extremely bright (V = 16.1), high-redshift (z = 2.88) QSO in an observing run at the ESO 2.2 m telescope in October 1995. The coordinates are $23^h 50^m 34.3^s$ $-43° 26' 00''$ (2000). The optical spectrum, spectral resolution ∼ 8 Å, is shown in Fig. 1. Because of the absence of damped Lyα lines and Lyman limit systems, HE 2347−4342 was immediately recognized as a candidate suitable for UV follow-up observations.

Table 1. The log of HST observations

Detector/ Grating	Spectral range	Aperture	Resolution FWHM	Exposure time (s)
Red G270H	2220–3240	4.″3	2 Å	1320
Red G190H	1620–2240	4.″3	1.5 Å	7930
G140L	1150–1440	LSA	0.7 Å	21106

Another low resolution spectrum (20 Å) was taken in October 1996 with the ESO 1.5 m telescope covering the wavelength range $\lambda\lambda$ 3200–9000 Å with the aim to obtain an improved QSO redshift. We find z = 2.870± 0.005 from the C III and C IV lines. However, we find a higher redshift of z = 2.885±0.005 in both low- and high-resolution spectra of the O I line. Since it is well known that the higher ionization lines underestimate the intrinsic QSO redshift, we shall use 2.885 hereafter.

HE 2347−4342 was observed twice with the Short Wavelength Prime (SWP) camera onboard IUE (SWP 56218, 580^m, 56228, 712^m). The QSO was detected in both images, although with very low signal-to-noise ratio at the 1–2 10^{-15} erg cm^{-2} s^{-1} Å^{-1} level.

With a flux more than a factor of 10 higher at the expected wavelength of the redshifted He II 304 Å line than in Q 0302−003 and PKS 1935−692 (cf. Jakobsen 1996), HE 2347−4342 offered the chance to observe the He II Lyα forest with the GHRS and the hope of resolving the He II forest.

2.2. UV observations with HST

The ultraviolet spectra have been taken in three visits between June 7 and June 14, 1996 with both the FOS in its high-resolution mode (R=1300) and the GHRS in its low resolution mode. The log of observations is given in Table 1. The standard pipeline processing provided flux calibrated data together with the 1σ error in the flux of each pixel as a function of wavelength. The maximum signal-to-noise ratio achieved for the GHRS observation is 14. With the GHRS first-order grating the background is mainly due to counts from particle radiation. Since the background is usually very low the average over all diodes is subtracted from the science data. Inspecting the raw science and background data we find a mean background level of 1–2 % of the mean quasar countrate.

The overall spectral energy distribution is shown in Fig. 1, together with a low resolution optical spectrum.

The strong break in the spectrum near 3500 Å is due to a Lyman limit system at z = 2.739 with an optical depth τ = 1.6, from which the flux recovers ($\tau_\nu \propto \nu^{-3}$) and rises to a maximum continuum flux at ∼ 1180 Å of ∼ 3.6 · 10^{-15} erg s^{-1} cm^{-2} Å^{-1} just longward of the He II break. HE 2347−4342 is nearly a factor of 2 brighter than HS 1700+6416 (Reimers et al. 1992) at the shortest wavelengths making it the most UV-bright high redshift quasar discovered so far.

In this paper we discuss only the strong He II absorption shortward of 1186 Å. A detailed analysis of the rich QSO ab-

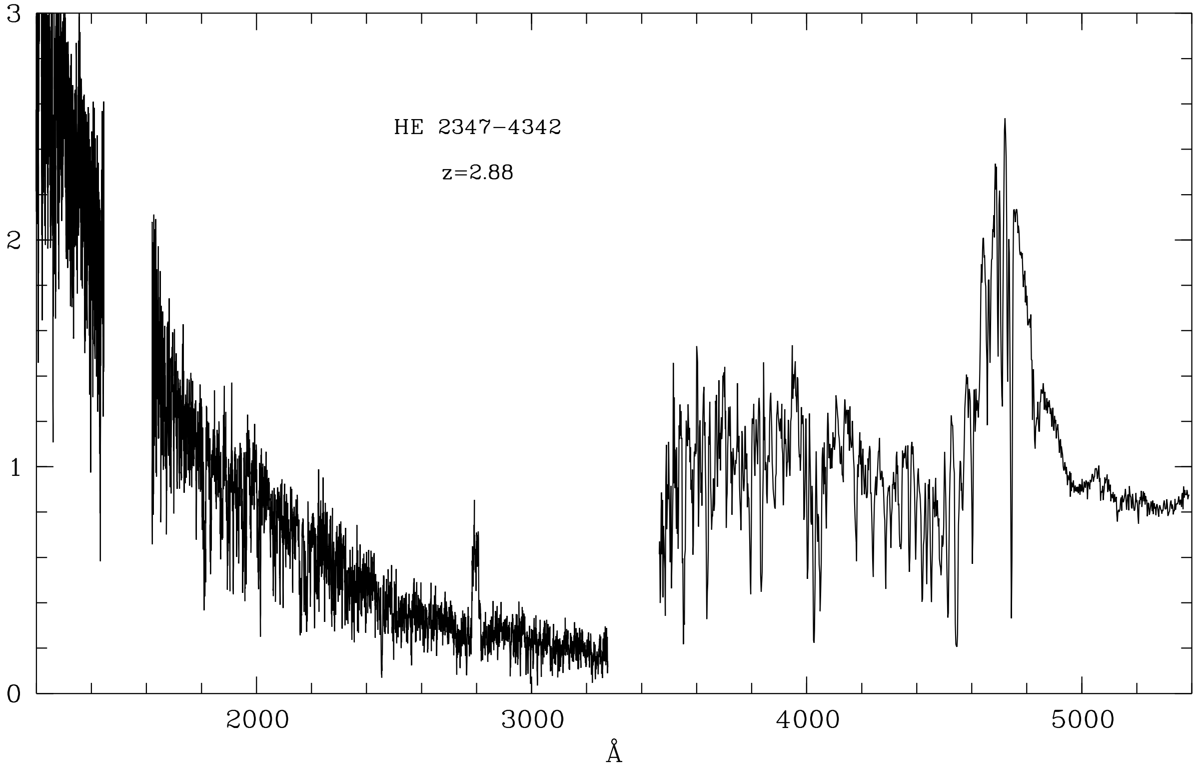

Fig. 1. Combined low-resolution optical spectrum observed with the ESO 2.2 m telescope and ultraviolet spectra obtained with the FOS and GHRS onboard the HST. Flux is given in units of 10^{-15} erg s^{-1} cm^{-2} Å^{-1}. The feature at 2800 Å is an artefact.

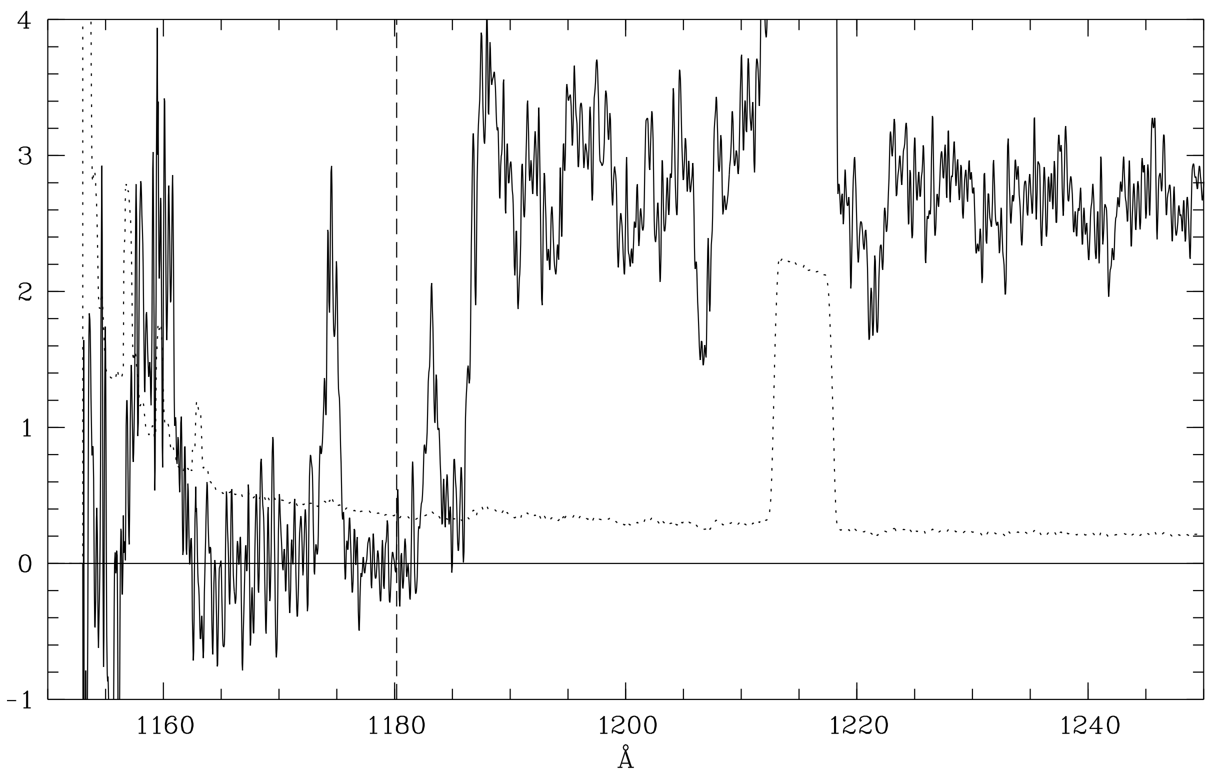

Fig. 2. Section of the GHRS spectrum and error spectrum (dotted curve) of HE 2347−4342 with the flux given in 10^{-15} erg s^{-1} cm^{-2} Å^{-1}. The expected position of the He II 303.78 Å edge for a QSO redshift of z = 2.885 is indicated by the vertical dashed line.

sorption line spectrum will be deferred to a future paper in which also the high-resolution optical spectra will be included.

Fig. 2 shows the relevant part of the GHRS spectrum. The absolute wavelength scale was checked using the strong interstellar lines Si II 1260 and C II 1335. We applied a wavelength zero point offset of −0.15 Å to shift the interstellar absorption lines to their rest wavelengths.

The first question we ask is whether the observed strong He II 303.78 Å edge is at the expected position. With an observed QSO redshift from the O I 1302 emission line in both low and high resolution spectra of $z = 2.885 \pm 0.005$, we expect the He II edge at 1180.2 ± 1.5 Å. The observed break is ∼ 6 Å to the red of this.

The explanation for this discrepancy is the presence of a strong multicomponent associated ($z_{\rm abs} \simeq z_{\rm em}$) absorption system with redshifts 2.8911, 2.8917, 2.8972, 2.8977, 2.8985, 2.8989, 2.9023, 2.9028 and 2.9041. This associated system is extremely strong in H I and in O VI and strong in N V, C IV and O V (cf. Fig. 3). In He II 303.78 two absorption complexes can be seen, the broad one ranging from 1184 to 1187 Å and the unresolved line pair z = 2.891 at 1182 Å (Fig. 4). The former is not saturated in He II, in contrast to H I and O VI, which means that He II is highly ionized close to the QSO. The apparent He II edge at 1186.5 Å and the absorption between 1182 and 1186.5 Å is exclusively due to the partially resolved He II lines of the associated system. Besides the highly redshifted associated systems with z = 2.891 to 2.904 (up to 1500 km s^{-1} relative to the QSO at z = 2.885) there are two further systems with highly ionized species: z = 2.878 (N V and C IV, unsaturated Lyα) and 2.863 (O VI, weak C IV, no N V, saturated Lyα). The latter again appears to show an unsaturated He II 303.8 Å line, like the redshifted associated system.

In summary, if the associated He II absorption is taken into account, the true observed He II edge is estimated to be around z = 2.889, cf. Fig. 3, close to the QSO emission redshift z = 2.885 ± 0.005.

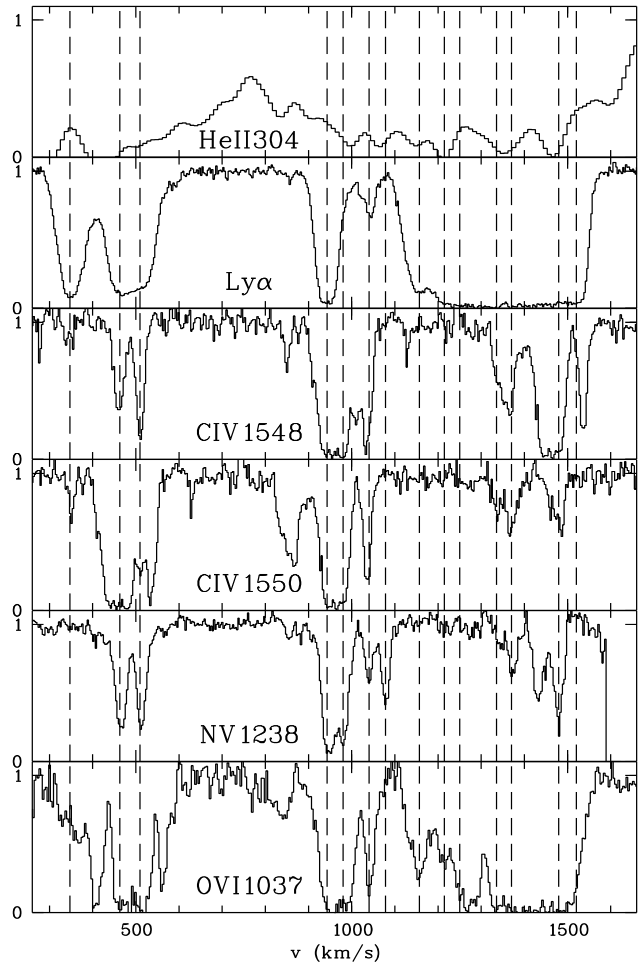

Fig. 3. Velocity profiles of absorption lines arising in the associated system as seen in the normalized high-resolution optical data. The velocity v = 0 km s^{-1} corresponds to a QSO redshift z = 2.885. At least 14 individual components can be identified by heavy element and/or H I Lyman series absorption lines. The complex associated system is responsible for the observed He II 303 Å absorption in HST data (cf. top panel) redward of the expected He II 303 Å edge at 1180±1.5 Å (corresponding to v = 0 km s^{-1}).

2.2.1. Continuum definition

The GHRS data were first corrected for interstellar reddening according to Seaton's law (Seaton 1979) with $E(B-V)$ = 0.0387, corresponding to N(H I)= 2.01 10^{20} cm^{-2} (Stark et al. 1992). A local continuum definition is difficult due to the high absorption line density. We searched for regions in the data apparently free of absorption lines, where we calculated the mean flux and the error in the mean flux to check for consistency with the noise. The continuum for the GHRS data was then constructed by fitting a low-order polynomial to these mean flux values. As is obvious from the GHRS data longward of the He II edge there are still numerous absorption lines presumable from heavy elements, since the number of Lyα clouds expected in this range is small at these low redshifts (Bahcall et al. 1993). Thus the derived continuum level might be underestimated due to unresolved line blending. This effect, however, should not influence the analysis of the He II absorption since it is expected to be of the same amount longward and shortward of the He II edge.

2.3. Optical observations and data reduction

HE 2347−4342 was observed on two nights (4–6 October 1996) using CASPEC with its Long Camera on the ESO 3.6 m telescope at La Silla. We obtained three individual 2h45m exposures in the spectral range from 3550 to 4830 Å and a single 2h45m exposure in the range from 4870 to 6180 Å. The slit was aligned with the parallactic angle in order to minimize light losses due to atmospheric dispersion. The data reduction was done with the ECHELLE software package available in MIDAS, supplemented by own software programmes for an optimal extraction of the echelle orders (kindly provided by S. Lopez).

For wavelength calibration, a Th-Ar comparison spectrum was obtained immediately before and after each QSO observation. For each order the wavelength scale was determined by fitting a third-order polynomial to the automatically identified lines. The resulting rms residuals were 0.003/0.005 Å for the two spectral regions. The individual observations were rebinned to the same wavelength scale and each observation was scaled by its median and then coadded, weighting by the inverse variance. After correction for the blaze function using observations of the standard star μColumbae, the continuum for each order was determined by fitting low-order polynomials to regions free of absorption lines. Wavelengths have been corrected to vacuum, heliocentric values. The final resolution achieved is R=21 500 with a signal-to-noise ratio of 34 per pixel at $\lambda_{\rm obs}$=4700 Å. For the single exposure longward of 4870 Å we reached R=24 500 and a S/N=14.

For a quantitative analysis of the He II edge we need to identify the corresponding H I Lyα clouds in the optical data. All absorption lines were fitted with Voigt profiles convolved with the instrumental profile using the software package FITLYMAN available in MIDAS to derive z, $N_{\rm H\,i}$ and b values. For the Lyα absorber clouds responsible for the observed part of the He II edge the optical data cover also Lyβ, Lyγ and Lyδ absorption lines allowing either an independent derivation of z, $N_{\rm H\,i}$ and b or at least a consistency check with the fit results for Lyα. With the available optical data we can detect Lyα absorption lines by neutral hydrogen down to column densities log $N_{\rm H\,i}$ = 12.6.

3. Interpretation

Are the observed Lyα forest clouds the main source of the observed strong He II opacity? This is addressed in Fig. 4 where the normalized high-resolution optical Lyα forest spectrum (scaled in wavelength according to 303.78/1215.67) is overlayed the normalized He II "forest" spectrum.

We note three different types of He II absorption regions:

- the associated systems (z = 2.891 to 2.904), which are strong in C IV, N V, O VI, and O V lines, can clearly be recognized in He II. The He II lines are partially resolved and weaker than H I Lyα.
- there are two "voids" in the Lyα forest spectrum which are also seen in He II: a void-like structure similar to the one in the Lyα forest of Q 0302−003 around 4 × 1160 Å with a width of $\sim$ 20 Å (5 Å in He II) and a further void at $\sim$ 4 × 1174.5 Å.
- in the remaining part of the He II spectrum, in the "troughs" at $\lambda\lambda$ 1163–1172 Å and 1176–1181 Å, there is no detectable flux in the He II forest ($\tau = 4.8^{+\infty}_{-2}$), and in particular there is no relation to the H I Lyα forest, in spite of several smaller "voids" in the Lyα forest (at 4 × $\sim$ 1180, 1171, 1164.5 Å). The 1163–1172 Å trough has a size of $\sim$ 6 h_{50}^{-1} Mpc (comoving) or 2300 km s^{-1}.

We have used the column densities, b-values and redshifts of the detected H I clouds to predict the He II absorption, adopting either turbulent or thermal line broadening. Simulated spectra were degraded to the GHRS resolution for a comparison with the observation. It is clear already from Fig. 4 that the three components ("voids", "troughs" and the associated system) cannot be modelled by scaling the Lyα forest clouds with one constant column density ratio $\eta = N_{\rm He\,ii}/N_{\rm H\,i}$.

This is shown in Fig. 5 where the model calculation assumes η = 100 and $b_{\rm He\,ii} = b_{\rm H\,i}$, i.e. pure turbulent broadening, which produces maximum He II opacity. While the two "voids" around 1160 and 1174 Å are perfectly matched - notice the structure within the 1160 Å void and the strong line on the short wavelength side of the 1174 void - the troughs cannot be modelled with the observed Lyα forest clouds, even for η = 1000. A continuous H I component with τ = 0.01 or a quasicontinuous blend of weak lines like the "undulating" absorption observed by Tytler (1995) in high S/N spectra of HS 1946+7658 could yield the observed He II opacity for η > 1000. However, whatever combinations of η and broadening parameters b are chosen, the "voids" and "troughs" cannot be modelled with the same parameter set.

As was shown already by Hogan et al. (1997), the observed Lyα clouds in the high-resolution optical spectrum of Q 0302−003 alone cannot explain the absorption even for extremely soft ionizing spectra. Since our optical data do not allow the detection of hydrogen clouds down to log $N_{\rm H\,i}$ = 12 cm^{-2}, we performed Monte Carlo simulations to estimate the amount of He II absorption by the weakest Lyα forest clouds. The distribution of Lyα clouds in redshift and column density was described by

$$\frac{\delta^2 N}{\delta N_{\rm HI}\, \delta z} = A\,(1+z)^{\gamma}\, N_{\rm HI}^{\beta} \qquad (1)$$

chosing A=2.4 10^7, γ = 2.46, β = −1.5 and $N_{\rm min}$ = 2 10^{12} cm^{-2} (e.g. Madau 1995 and references therein). But even for η = 1000 and turbulent broadening we reach the same conclusion as Hogan et al. (1997).

As far as the associated system is concerned, we expect a much harder ionizing spectrum due to the quasar, i.e. lower values of η. Considering both heavy element and hydrogen absorption lines in the optical data we can distinguish 14 individual components of the associated system ranging from z = 2.8896 to 2.9047, i.e. spanning $\approx$ 1000 km s^{-1}. For absorber components with the strongest H I absorption (i.e. those at z > 2.8985) the observed He II absorption is best modelled adopting η = 5 for $b_{\rm He\,ii} = b_{\rm H\,i}$, while at lower redshift (z = 2.8896–2.8985) η = 100 is more appropriate. According to our estimates for the spectral shape of the intrinsic quasar energy distribution (see below) we would expect $\eta \approx$ 8.

We conclude from the above that the ionization structure of the associated systems also cannot be modelled by a single set of parameters (cf. discussion in Sect. 3.4).

3.1. "Voids"

3.1.1. Pure Lyα forest opacity

Fig. 5 shows that the "void" at 1160 Å can be explained by photoionized forest clouds far from the QSO with η = 100 and

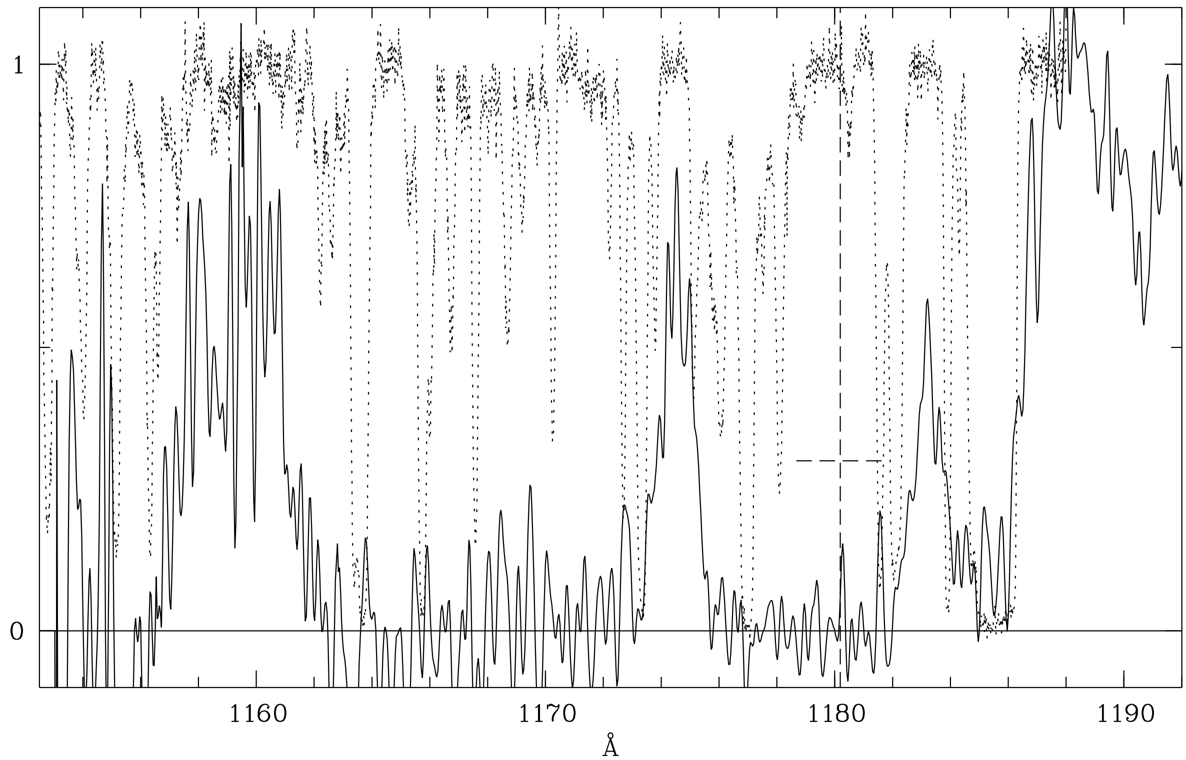

Fig. 4. He II 304 Å forest as seen in the normalized GHRS spectrum overlaid with the corresponding H I Lyα forest in the normalized high-resolution optical data (dotted curve) scaled in wavelength according to 303.78/1215.67. The expected position of the He II 303.78 Å edge according to a QSO redshift of z = 2.885 ± 0.005 is indicated by the dashed lines.

turbulent broadening $b_{\rm He\,II} = b_{\rm H\,I}$. This high value of η is barely consistent with models of an ionizing metagalactic background due to QSOs which predict η = 45 (Haardt & Madau 1996). However, the faint end of the QSO luminosity function is not known for $z > 3$ and there may be a contribution by stars (Rauch et al. 1997). This "void" component is consistent with what Davidsen et al. (1996) found at lower redshift z = 2.4 in HS 1700+6416.

3.1.2. Lyα forest plus diffuse component

Assuming instead $\eta \simeq 45$ (Haardt & Madau 1996) and pure thermal broadening of He II, for which there is evidence from theoretical Lyα forest simulations (e.g. Zhang et al. 1997), the known Lyα forest clouds in the 1160 Å void contribute only ∼ 50 % of the observed opacity and an additional optical depth $\tau^{\rm GP}_{\rm He\,II} \simeq 0.3$ is required (see Fig. 6). The latter includes the contribution by faint optically thin forest lines not detected in our high-resolution spectrum. According to Madau & Meiksin (1994) the optical depth $\tau_{\rm GP}$ of the diffuse He II gas is related to the background intensity in photoionization equilibrium by

$$\Omega_{\rm diff} = 0.25 \cdot \tau_{\rm GP}^{0.5} \cdot h_{50}^{-1.5} \cdot S_{\rm L}^{-0.5} \cdot J_{-21}^{0.5} \quad (2)$$

where J_{-21} is the mean intensity of the ionizing background at 912 Å in units of 10^{-21} erg cm^{-2} s^{-1} Å^{-1} sterad^{-1}, h_{50} is the Hubble constant in units of H_0 = 50 km s^{-1} Mpc^{-1} and q_0=0.5. With $\tau_{\rm GP}^{\rm He\,II} = 0.3$, $J_{-21} = 0.5$, $\eta = 45$ ($S_{\rm L} = \eta/1.8$) Eq. (2) yields $\Omega_{\rm diff} = 0.02\ h_{50}^{-1.5}$. Because of the assumed lower limit to a He II forest contribution, this must be considered as a strict upper limit.

Our result for the void at 1160 Å is also consistent with the diffuse gas density derived by Hogan et al. (1997) for the void in Q 0302−003 at z = 3.17. They found $2 \le \tau \le 1.3$ for the diffuse component. With the same parameters used in this paper this translates to $0.043\ h_{50}^{-1.5} \ge \Omega_{\rm diff} \ge 0.035\ h_{50}^{-1.5}$ for η = 45 and $0.029\ h_{50}^{-1.5} \ge \Omega_{\rm diff} \ge 0.023\ h_{50}^{-1.5}$ for η = 100, respectively. The latter softer ionizing spectrum appears more appropriate at z = 3.17 (Songaila & Cowie 1996) and is consistent with the diffuse density $\Omega \simeq 0.02\ h_{50}^{-1.5}$ derived at z = 2.82 in HE 2347−4342. With the same shape of the ionizing background at z = 2.8 and z = 3.17, the diffuse density found in the HE 2347−4342 void is lower by a factor of 2 than in the Q 0302−003 void.

If the voids are caused by additional ionizing sources – and we have no better explanation for voids in the Lyα forest – the background radiation may be irrelevant for the ionization in the voids. In case of an AGN as ionizing source, η would be smaller ($\eta \le 10$) and the necessary amount of diffuse gas would increase. A star dominated ionizing source, on the other hand would mean a larger η (≥ 100) and no diffuse medium would be required. We must conclude that at present we have no real constraints for a diffuse medium in the voids.

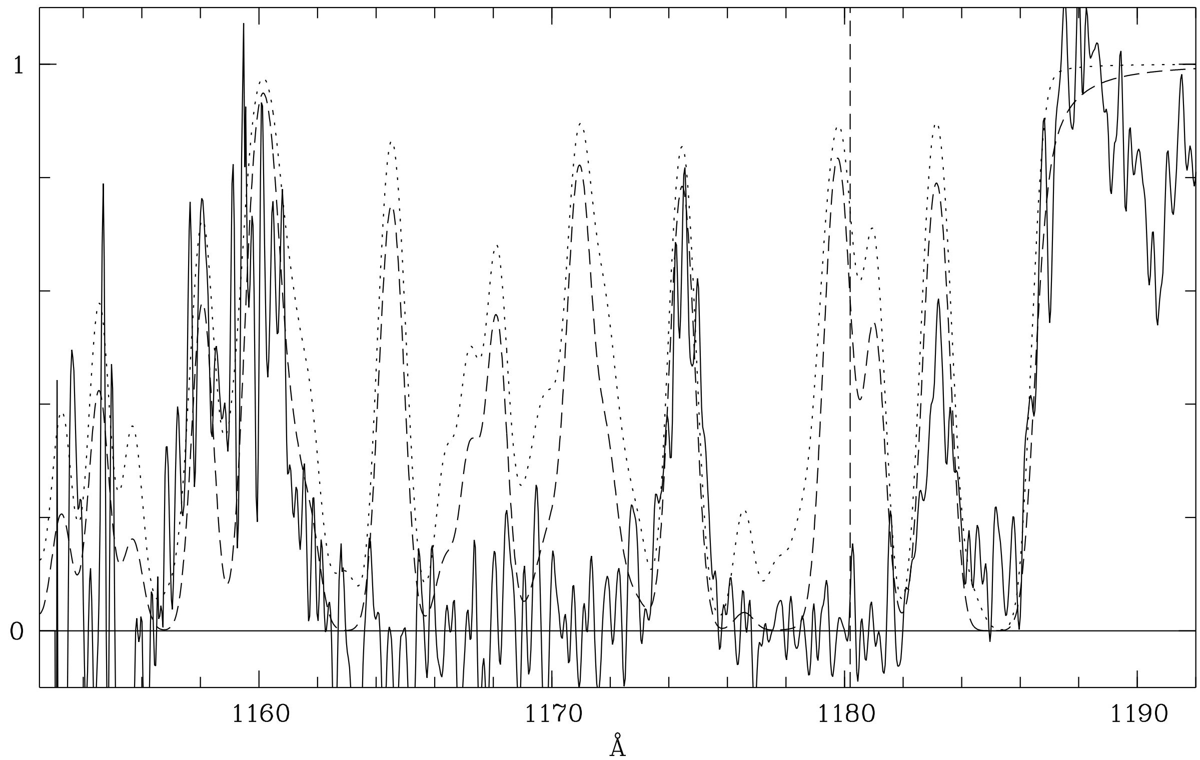

Fig. 5. The normalized GHRS spectrum overlaid with the model He II absorption spectrum predicted on the basis of redshifts, H I column densities and velocity dispersion parameters of the Lyα forest lines detected in the optical data. The dotted (dashed) curve corresponds to the assumptions $N_{He\,\rm II}/N_{H\,\rm I}$ = 100 (1000) and pure turbulent broadening $b_{He\,\rm II} = b_{H\,\rm I}$.

3.2. The "troughs"

The mean flux measured from our data in the wavelength range from 1175.5 to 1181 Å is $f_\lambda = 0.023 \pm 0.18\,10^{-15}$ erg s^{-1} cm^{-2} Å^{-1}. The continuum flux measured just longward of the He II edge is $f_\lambda = 3.6\ 10^{-15}$ erg s^{-1} cm^{-2} Å^{-1}. The corresponding flux ratio implies a high optical depth $\tau = 5$. When the flux depression by discrete He II absorption of Lyα forest clouds is taken into account the minimum required optical depth is $\tau \approx 4.8^{+\infty}_{-2}$ to explain the vanishing flux.

If the same ionizing UV background is responsible for the ionization in the "troughs" the density of the diffuse gas can easily be estimated. According to Eq. 2, $\tau > 4.8$ (2.8) yields $\Omega_{\rm diff} > 0.077$ (0.059) $h_{50}^{-1.5}$ ($\geq$ 0.03 (0.023) $h_{50}^{-1.5}$ for η = 250) close to the total big bang nucleosynthesis baryon density $\Omega_{\rm bb} = 0.05\ h_{50}^{-2}$ (Walker et al. 1991). Assuming that the He II opacity in the "troughs" represents the normal IGM at $z = 2.85$ and the "void" at 1160 Å is caused by higher ionization due to additional local ionizing sources, we are forced to conclude that the baryons are largely in the diffuse or at least the low density part of the IGM. This would be at variance with all recent hydrodynamical simulations of hierarchical structure formation (Cen et al. 1994; Miralda-Escudé et al. 1996; Zhang et al. 1997; Rauch et al. 1997; Meiksin 1997) which predict that except a few percent all of the baryons are in the Lyα forest clouds, i.e. fragmentation of the IGM should be nearly complete.

There is a further argument against photoionization of the trough component by the same ionizing radiation as the voids. Since τ(H I)= 4 τ(He II)/η, the Gunn-Peterson constraints τ(He II) $\geq$ 2.8 (4.8) and τ(H I) $\leq$ 0.05 lead to $\eta \geq$ 220 (380), which is inconsistent with an AGN dominated background at $z \leq 3$ for which there is ample evidence (e.g. Haardt & Madau 1996).

Trying to explain the observed flux depression, e.g. at 1180 Å, we also estimated the contribution from further absorber candidates like a) He II absorption from weak Lyα clouds which are not detectable in our data, b) higher Lyman series lines from Lyα clouds at low redshifts, c) neutral helium absorption or d) heavy element absorption lines. Of course none of these absorption lines alone can account for the total absorption observed.

In our calculation we considered at the same time a) a diffuse He II absorbing component with τ=0.2, b) He I 584 absorption from the strong Lyα clouds detected at $z = 1$, c) He II absorption lines from presumed weak Lyα forest clouds with log $N_{\rm H\,i}$ = 12 adopting η = 100 in addition to He II absorption from detected Lyα forest clouds. Unless one assumes $N_{\rm He\,ii}/N_{\rm H\,i}$ = 1000 all these absorbers cannot explain the vanishing flux.

Further absorption turning on just at the He II edge is expected by the strong O III doublet at 303 and 305 Å. Down to $z_{\rm abs}$ = 2 it is possible to identify MLS by C IV absorption longward of Lyα emission in the optical data. Besides the associated system we identified 9 MLS, which often split into several com-

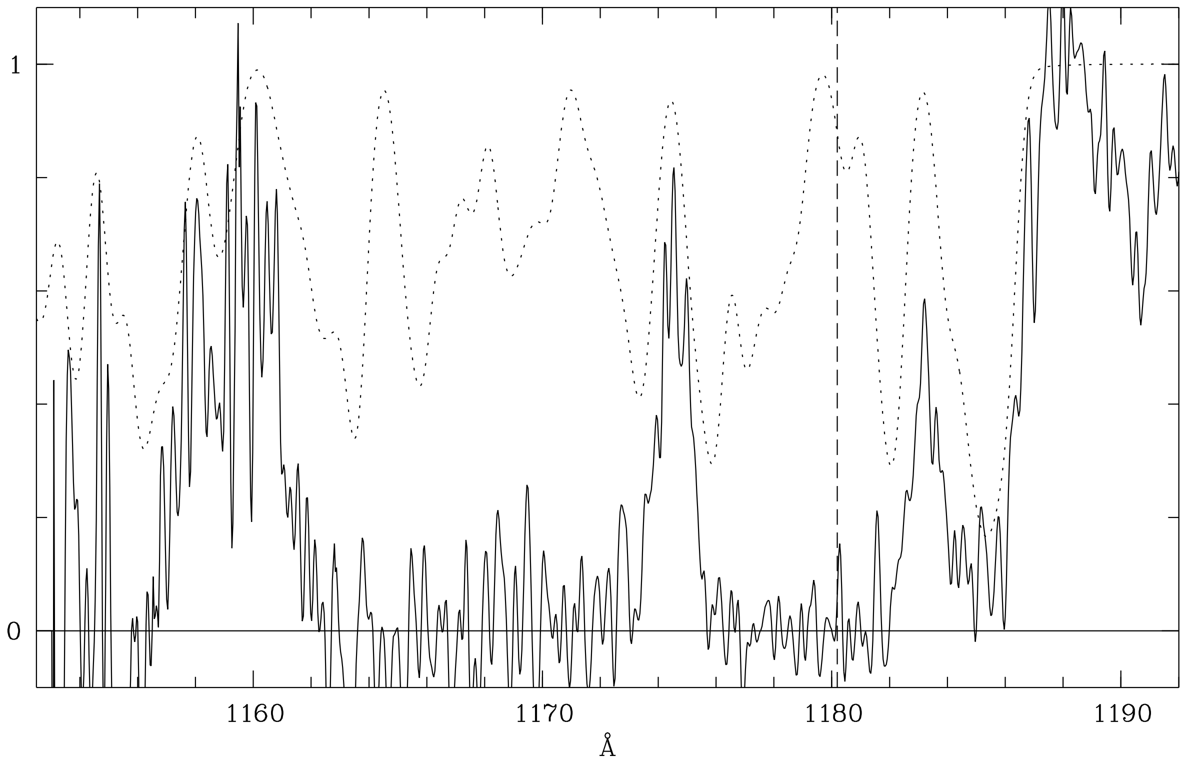

Fig. 6. Normalized part of the GHRS spectrum overlaid with a model He II absorption spectrum predicted on the basis of redshifts, H I column densities and velocity dispersion parameters from Lyα forest lines in optical data. The dotted curve corresponds to the assumptions $N_{He\,\mathrm{II}}/N_{H\,\mathrm{I}}$ = 45 and pure thermal broadening $b_{He\,\mathrm{II}}$ = 0.5 $b_{H\,\mathrm{I}}$.

ponents. For absorbers with $z > 2.8$ the O III 303,305 doublet falls longward of 1150 Å. We calculated simple CLOUDY (Ferland 1993) models to estimate their influence. Unless adopting very unrealistic high column densities for O III these lines cannot explain a total absorption.

3.3. Delayed He II ionization

We see only one way to resolve the observed inconsistencies: He II ionization in the "trough" component has to be incomplete. Meiksin & Madau (1993) have predicted H I absorption "troughs" with vanishing flux, velocity broadened by the Hubble expansion. This has so far not been seen in H I up to z = 4.9. We propose here that we observe a patchy intergalactic medium in which the reionization of the universe is still incomplete at $z \simeq 3$ for the second ionization of He. This possibility has been predicted by various authors, e.g. Miralda-Escudé & Rees (1993) and Madau & Meiksin (1994). The reason for the delayed ionization of He II is the much smaller number of He II ionizing photons compared to H ionizing photons. Madau & Meiksin (1994) show that with QSO spectra varying as $\nu^{-1.9}$ and the quasars turned on at z = 6, hydrogen is fully ionized at z = 5, but that He II is only partially ionized at z = 3. According to recent work by Shaver et al. (1996), QSOs are an order of magnitude less abundant at $z > 4$ than at $z < 3$, i.e. the turnon of the QSOs as ionizing sources is even later than assumed by Madau & Meiksin (1994). Furthermore, there is evidence from modelling of the Lyα forest that for $z > 3$ the UV-background due to QSOs is not sufficient and that additional sources of photons are required for $z > 3$ (Rauch et al. 1997). If these sources are stars, the resulting softer UV background possibly meets the condition for delayed He II ionization. In addition, it has been shown by Giroux & Shapiro (1996) that in case of an IGM partially collisionally ionized due to bulk heating in addition to photoionization, He ionization will be lag behind hydrogen ionization. There is also evidence of an abrupt change in the C IV/Si IV column density ratio around z = 3 (Songaila & Cowie 1996), which indicates a softening of the ionizing UV background with increasing z: $\eta \approx$ 20 to 40 below z = 3.1 and $\eta >$ 250 above z = 3.1.

In case of only singly ionized helium, the amount of diffuse gas needed to produce the "trough" opacity $\tau_{\mathrm{GP}}^{\mathrm{He\,ii}} \geq 4.8$ is given by

$$\tau_{\mathrm{GP}}^{\mathrm{He\,ii}}(z = 2.8) = 3.6 \cdot 10^4 \cdot \Omega_{\mathrm{diff}} \cdot h_{50} \qquad (3)$$

for q_0 = 0.5 (Madau & Meiksin 1994) which leads to $\Omega_{\mathrm{diff}} \geq 1.3 \cdot 10^{-4}\ \mathrm{h}_{50}^{-1}$. Only 0.3 % of the big-bang nucleosynthesis baryon density $\Omega_{\mathrm{bb}} = 0.05\ \mathrm{h}_{50}^{-2}$ is required to produce the blacked-out troughs. This would be consistent with the theoretical predictions that fragmentation of the IGM is nearly complete.

It is easy to show that even for a soft ionizing spectrum (α = 2) the "troughs" will not be seen in He I 584 Å since

$N_{\rm He\,i}/N_{\rm He\,ii} \simeq 2 \cdot 10^{-7}$ for $\Omega = 0.02$ (cf. Jakobsen 1995). The FOS spectrum around 2240 Å confirms the absence of a He I trough.

3.4. No proximity effect?

An extremely luminous QSO like HE 2347−4342 is expected to show a proximity effect except for the rather improbable case that the QSO has been turned on only recently.

The influence of the UV radiation of the QSO itself on the second ionization of He has been studied theoretically by various authors (e.g. Zheng & Davidsen 1995; Meiksin 1995; Giroux et al. 1995). The prediction is that close to the QSO He II is additionally ionized and that the effect is stronger in diffuse than in clumped gas. Consequently, if the He II opacity close to the QSO is dominated by a diffuse component, we expect increased transparency in a He III bubble around the QSO, close to the rest redshift of the QSO, while the effect will be weaker in the Lyα forest. No proximity effect has been seen in HS 1700+6416 (Davidsen et al. 1996), while Hogan et al. (1997) observed in Q 0302−003 a "shelf" in the He II opacity $\sim$ 12 Å blueward of the main He II edge which they interpret as a proximity effect in diffuse He II gas. If, as concluded above, the "troughs" in the He II forest at 1162–1173 Å and 1176–1182 Å are caused by not fully ionized gas, we should expect that HE 2347−4342, which at the time of observation is one of the most luminous sources in the universe, produces a strong proximity effect.

In the following we estimate the He II ionizing flux of HE 2347−4342 and discuss its effect on the surrounding medium. UV spectra of high-redshift quasars are strongly influenced by absorption of intervening absorbers. In order to find the intrinsic spectral energy distribution of the quasar corrections have to be applied to the observed data. In the following we will consider only the flux depression by cumulative hydrogen continuum absorption of intervening absorbers, neglecting effects of dust absorption along the line of sight or line blanketing in the UV. Uncertainties in the absolute flux calibrations of the spectra up to 10–20 % are possible.

The dereddened spectra of HE 2347−4342 were corrected for continuum absorption by neutral hydrogen in the strong LLS at $z = 2.739$. The continuously rising spectrum of HE 2347−4342 shows no evidence for further strong absorbers with log $N_{\rm H\,i} > 16$. The additional "Lyman valley" depression of the quasar continuum due to the cumulative hydrogen absorption by the numerous Lyα clouds with $12 \leq \log N_{\rm H\,i} \leq 16$ was estimated by Monte Carlo simulations. Since $\lambda_{\rm rest}$ = 228 Å is not directly observable, we take the corrected continuum value at the smallest observed wavelength ($\lambda_{\rm rest}$ = 298 Å), assuming that it is close to the flux at 228 Å. We find f_λ(885.78 Å) $\approx$ f_λ(1157 Å) = 6.4 10^{-15} erg s^{-1} cm^{-2} Å^{-1}, i.e. nearly a factor of 2 higher than the observed flux.

For the QSO flux at $\lambda_{\rm rest}$ = 912 Å we considered the flux in the range from 3560 to 3580 Å in the optical data just longward of the corresponding but unobserved wavelength 3.885 × 912 = 3543 Å. Since in low-resolution optical data the flux is depressed by unresolved line blanketing of Lyα forest lines, we rebinned our high-resolution optical data to estimate the flux depression by line blending. The resulting flux is then f_λ(3543 Å)=1.75 10^{-15} erg s^{-1} cm^{-2} Å^{-1} yielding a ratio of $S_{\rm L} = f_\nu(912)/f_\nu(228)$ = 4.4. Adopting a pure power law ($f_\nu \propto \nu^\alpha$) for the intrinsic EUV spectral energy distribution $S_{\rm L}$ = 4.4 turns into $\alpha = -1.0$, which is a typical value for several luminous QSOs observed with HST (Köhler & Reimers 1996). In the proximity of the quasar we thereby do not expect a strong contribution from diffuse Helium. With

$$\tau_{\rm GP}^{\rm HeII} \sim 0.45\, S_{\rm L}\, \tau_{\rm GP}^{\rm HI} \tag{4}$$

(Madau & Meiksin 1994) and $\tau_{\rm GP}^{\rm HI} < 0.05$ (Giallongo et al. 1994) we expect for $S_{\rm L}$ = 4.4 an optical depth of the diffuse component $\tau_{\rm GP}^{\rm HeII}$ = 0.1 comparable to $\tau_{\rm GP}^{\rm HeII} \leq 0.3$ derived from the observations. For the associated system we would expect $N_{\rm He\,ii}/N_{\rm H\,i} = 8$ ($\eta = 1.8\,S_{\rm L}$) also consistent with the observation at least for the components at highest redshifts when adopting turbulent line broadening.

For a QSO flux at the He II edge of f_ν = 1.7 10^{-27} erg s^{-1} cm^{-2} Hz^{-1} at z = 2.885 (for f_λ(1157 Å)=6.4 10^{-15} erg s^{-1} cm^{-2} Å^{-1} as derived above and Eq. 6 from Giroux et al. 1995) we get $f_{\rm q}$ = 1.1 10^{-21} erg s^{-1} cm^{-2} Hz^{-1} at $z_{\rm abs}$ = 2.819 (corresponding to He II 304 absorption at 1160 Å) which has to be compared with a background flux $f_\nu = J_\nu \cdot 4\pi$ = 2.5 10^{-22} erg s^{-1} cm^{-2} Hz^{-1} (Haardt & Madau 1996) or f_ν = 1.5 10^{-21} erg s^{-1} cm^{-2} Hz^{-1} (Bechtold 1995 with $S_{\rm L} = f_{912}/f_{228}$ = 25). This means that HE 2347−4342 with its observed hard ($\alpha = -1$) EUV spectrum dominates He II ionization at least up to the λ 1160 Å void. This is not observed. Why does HE 2347−4342 ionize He II in the associated system but not in the troughs, in particular the region $\lambda\lambda$1176–1180 Å? There is only one plausible reason for the nonexistence of a proximity effect in He II: shielding by clouds optically thick in the He II 228 Å continuum along the line of sight. Possible candidates are the associated system clouds.

A reliable estimate of the neutral hydrogen column densities of the individual components of the associated system is difficult due to the complex structure of the system and saturation effects. Higher Lyman series lines up to H I 920 are visible, but the signal to noise ratio of our spectrum decreases rapidly at shorter wavelengths. According to absorption line fits the largest column density for a single component should not exceed log $N_{\rm H\,i} \approx 16$ for $b_{\rm min}$ = 20 km s^{-1}. From optical data we cannot preclude the existence of a small break at the Lyman edge expected at $\approx$ 3550 Å. The maximum total H I column density compatible with the optical data is then $\approx$ 6 10^{16} cm^{-2} . With the H I column densities derived from modelling of Lyman series lines adopting $b > 20$ km s^{-1} for the 14 individual components the observed He II absorption requires $\eta > 45$ for thermal line broadening. Thus for a single component with log $N_{\rm H\,i}$ = 16 and $\eta > 45$ we find $N_{\rm He\,ii} > 4.5$ 10^{17} cm^{-2}. The clouds become optically thick for He II at a column density 6.3 10^{17} cm^{-2} and self shielding could enhance the He II absorption. In fact, as was mentioned in Sect. 3, η = 100 gives a better fit for the lower redshift components (z = 2.8896–2.8985) which leads to possibly $N_{\rm He\,ii} \geq 10^{18}$ cm^{-2}, sufficient to shield the IGM in our direction from He II ionizing photons. A detailed analysis of the associated system with better optical data will help to improve the constraints for the He II continuum absorption.

What is the origin of the 1160 Å and 1174 Å voids? If the troughs are due to unionized He II which completely shields the EUV background at $\lambda \leq 228$ Å, we have to assume that individual sources (QSO and/or starburst galaxies) create He III regions within the unionized IGM. With a diameter of 2.8 h_{50}^{-1} Mpc for the 1160 Å void, the requirements on the luminosities of possible sources are moderate (cf. Bajtlik et al. 1988, Giroux & Shapiro 1996). The observed $\eta \geq 45$ would favour at least a contribution by stars in the ionizing source.

4. Summary and conclusions

We have shown that the IGM in the line of sight of HE 2347−4342 is "patchy" in the sense that there are "voids" and "troughs". In the voids, the He II opacity can be understood as Lyα forest line opacity with either $\eta = 100$ and $b_{\rm He\,ii} = b_{\rm H\,i}$ and no diffuse medium or Lyα forest line opacity with $\eta = 45$ and $b_{\rm He\,ii} = 0.5\,b_{\rm H\,i}$ plus a diffuse medium with $\tau_{\rm GP} = 0.3$. The He II opacity seen in the voids is consistent with what has been found in HS 1700+6416 (Davidsen et al. 1996) or in the Q 0302−003 void by Hogan et al. (1997). In the "troughs" we need in addition to the He II Lyα forest opacity a continuous opacity of $\tau_{\rm GP}^{\rm He\,ii} > 4.8$ ($\tau > 2.8$ is a strict lower limit). A natural explanation for this dichotomy is the assumption of delayed He II ionization, as predicted by e.g. Madau & Meiksin (1994), where in the phase of reionization of the universe there are still not yet ionized He II regions between the expanding He III regions. In that case $\Omega_{\rm diff} \geq 1.3 \cdot 10^{-4}\ h_{50}^{-1}$ would be necessary. The absorption troughs have the shape and widths as predicted by Meiksin & Madau (1993).

The patchy He II opacity appears to be the "missing link" between the $\tau = 1$ at $\bar{z} = 2.4$ in HS 1700+6416 and the high opacity in Q 0302−003 at $z = 3.2$: The "voids" in HE 2347−4342 have optical depths comparable to the mean opacity observed in HS 1700+6416 and represent the reionized IGM, while the "troughs" represent the IGM with delayed He II reionization which may also be the case for Q 0302−003 and PKS 1935−692 at $z \gtrsim 3.1$. It is important to repeat the He II opacity measurement in case of Q 0302−003 with STIS because the background subtraction procedure applied to the GHRS data appears doubtful at such low flux levels.

Our He II observations are in accordance with Songaila and Cowie's (1996) finding from the observed C IV/Si IV ratio as a function of redshift that around $z = 3$ there appears to be a transition from a soft ionizing UV background ($z > 3$) to relatively hard ionizing radiation ($z < 3$). If confirmed by further observations, the delayed He II ionization gives important constraints on the evolution of the UV background for $z > 3$.

The same ionization model of Madau & Meiksin (1994) which predicts incomplete He II ionization for $z \geq 3$ predicts incomplete H I ionization for $z \geq 4.9$. After our observation of delayed He II ionization there appears to be a realistic chance to observe directly the phase of reionization of the universe if $z \geq 5$ QSOs exist since the latter might show H I blacked-out troughs similar to what we have seen in He II. One has to keep in mind, however, that HE 2347−4342 is just one line of sight, and that before generalizations are possible, more objects have to be probed.

The absence of a measurable proximity effect in HE 2347−4342 might be explained by shielding of $\lambda < 228$ Å radiation by the clouds responsible for the strong associated system seen toward this quasar.

Observations of the He II troughs in HE 2347−4342 with STIS in low resolution can be expected to yield an improved lower limit to the diffuse density in the yet unionized medium, and HE 2347−4342 is even bright enough in the 1160 Å void for FUSE to resolve directly the He II 304 Å forest.

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