Resolving the Helium Lyman-α Forest: Mapping Intergalactic Gas and Ionizing Radiation at $z \approx 3^1$

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ABSTRACT

We present a new, high resolution HST/GHRS spectrum of quasar Q0 302-003, and use the $He^+$ Lyman-$\alpha$ absorption, together with a high resolution Keck spectrum of the $HI$ Lyman-$\alpha$ forest, to probe the distribution and ionization state of foreground gas just below the quasar redshift $z \approx 3.3$. Within $\approx 4000$ km/sec of the quasar redshift the spectrum shows a substantial flux ($\tau \approx 1$) with “$He^+$ Lyman-$\alpha$ forest” absorption features correlated in redshift with the $HI$ Lyman-$\alpha$ forest; the absorption in this region is accounted for entirely by the discrete components of the forest, indeed the main “Gunn-Peterson edge” can be identified with a particular complex of HI absorbing clouds. We attribute the lack of continuous absorption from diffuse gas to the “proximity effect” in this region, a large bubble where helium is highly ionized by the quasar, and use its size to estimate the background flux at the $He^+$ ionization threshold. The near-quasar data also lead to constraints on diffuse gas density near the quasar, tied to the observed quasar flux, and helium abundance, tied to the observed quasar spectrum. Far from the quasar redshift, the spectrum displays $He^+$ absorption ($\tau \geq 1.3$) even in several redshift intervals with no detectable HI absorption, implying a soft ionizing spectrum as well as absorption from gas between detected HI clouds. The smoothed spectrum displays residual flux everywhere with an average optical depth $\tau_{GP} \leq 2$, which indicates a low density of redshift-space-filling gas; using constraints from the HI ionizing spectrum we estimate $\Omega_g \leq 0.01(h/0.7)^{-1.5}$, and infer that the helium is already mostly doubly ionized by this epoch. Our estimates are consistent with ionization models based on observed quasar populations, previous limits from HI Gunn-Peterson studies, and simulations of the gas distribution in CDM models of galaxy formation.
1. Introduction

The line of sight to the $z = 3.285$ quasar Q0302-003 (hereafter, Q0302) provides a unique probe of the intergalactic medium at high redshift. It is the highest redshift quasar yet discovered where the light is unobscured down to below 304 Å in the rest frame, allowing measurement of $\text{He}^+$ Lyman-α absorption by foreground gas. Besides confirming the abundant primordial helium predicted by the Big Bang model, the helium absorption records new information about the ionization history of intergalactic gas, especially useful for disentangling the roles of stars and quasars in reionizing the universe. Most significantly, its relatively higher optical depth provides a better tool than HI for measuring absorption by diffuse gas which fills the space between the galaxies and between the identified HI “Lyman-α forest” clouds, in the intergalactic and protogalactic media. Resolved helium absorption provides a direct “nonlinear map” of the gas distribution in the most rarefied gas occupying most of the volume of space.

Ideas about the cosmic gas distribution have sharpened quantitatively in recent years, due to hydrodynamic simulations which accurately predict the motion of matter in hierarchical models of galaxy formation (Cen et al. 1994, Hernquist et al. 1995, Miralda-Escudé et al. 1996, Rauch et al. 1997, Croft et al. 1997, Zhang et al. 1997; see also Bi and Davidsen 1997). Departing from earlier models based on isolated clouds with symmetric geometries such as spheres and slabs, simulations of the conversion of uniform gas into condensations reveal a dynamical system with a complex geometry where the distinction between diffuse gas and clouds is blurred and is not always reflected in the appearance of an absorption spectrum. Simulated spectra reveal that gas in the most underdense regions, filling the bulk of the spatial volume, is so highly ionized that it produces absorption features with very low HI Lyman-α optical depth. The most abundant ion $\text{He}^+$ however produces optical depths of the order of unity even in these regions, so its
absorption is easily detectable, mapping the distribution of cosmic baryons at the lowest densities.

Absorption by He$^+$ is also the most direct probe of the hard ultraviolet cosmic radiation field, which can be predicted from semiempirical models based on observed quasar and absorber populations (Haardt and Madau 1996). The spectral shape also influences other observables such as the ratio of CIV to SiIV (Songaila & Cowie 1996, Giroux & Shull 1997, Savaglio et al. 1997), so information from helium absorption allows information about relative C and Si abundances to be derived. In situations where the ionizing spectrum is known, such as the near proximity of a quasar, He$^+$ absorption can be compared to HI absorption to extract independent information about the primordial abundance of helium, an important test of Big Bang Nucleosynthesis.

The first detection of cosmic He$^+$ absorption was made in Q0302 by Jakobsen et al. using the Hubble Space Telescope Faint Object Camera (FOC). They found an absorption edge and a large “Gunn-Peterson” continuous optical depth, $\tau > 1.7$, attributed to He$^+$ Lyman-\(\alpha\) absorption by diffuse gas. A similar observation has also been made of the $z = 3.185$ quasar PKS 1935-692, with a similar result (a lower limit on the optical depth $\tau > 1.5$, also at 90% confidence, by Tytler & Jakobsen 1996; note that this result is based on new data which modify earlier conclusions on this object by Tytler et al. 1995). These data however had important limitations; the low (10 Å) resolution of the FOC could not resolve features from the known HI clouds or even from the larger gaps between them, and the inaccuracy of the calibration (20 Å) could not place the location of the edge accurately relative to either the quasar or the clouds.

A significant improvement came from the Hopkins Ultraviolet Telescope (Davidsen et al. 1996), which can reach shorter wavelengths and hence lower redshift than HST, and also provides better resolution and wavelength calibration than FOC. Davidsen et al. observed
the $z = 2.72$ quasar HS 1700+64 and found an $He^+$ edge close enough to the predicted redshift to rule out the possibility of foreground HI as an important contaminant. They also found that the flux below the edge is not consistent with zero, and measured accurately a mean optical depth, $\tau = 1.00 \pm 0.07$. The decreasing absorption with time reflects the increasing ionization of $He^+$ at around $z = 3$ and the conversion of diffuse gas into clouds.

Our new observations of Q0302 were made to improve both the wavelength calibration and resolution of the $He^+$ absorption, with enough sensitivity to correlate usefully with the HI absorption. This is much more informative than just detecting the mean absorption—we can explore the relative contributions of clouds and diffuse gas, as well as measuring independently the ionizing radiation field and the helium abundance. A substantial optical depth, on the order of the whole effect detected at low resolution (Songaila et al. 1995), is expected just from the gas accounted for in the discrete clouds already identified as the HI Lyman-$\alpha$ forest. Although this possibility can be modeled theoretically in a statistical way for low resolution data (Giroux et al. 1995), our higher resolution $He^+$ spectrum allows a direct detailed comparison between HI and $He^+$ line absorption, and hence a much more powerful constraint on models. We find significant $He^+$ absorption from HI clouds (with optical depth of the order of unity) but also comparable $He^+$ absorption even in redshift intervals where the best Keck spectrum reveals no detectable HI; thus we directly measure absorption attributable separately to both the clouds and the diffuse gas. Even with high resolution however our spectrum suggests nonzero flux at all wavelengths, which constrains the ionizing background spectrum and leads to an upper limit on the density of diffuse gas. Absorption from gas near the quasar, where the incident spectrum is known approximately from the direct measurement of the quasar spectrum, allows independent constraints on the density and helium abundance of the gas.
2. Observations and Reductions

On 3 separate visits in October, November, and December of 1995, Q0302 was observed with the Goddard High Resolution Spectrograph (GHRS). The G140L grating and “D1” detector were chosen especially because of their high UV efficiency, but this setup also provides good spectral resolution of 0.6 Å (about one diode). Q0302 is too faint for a direct target acquisition with GHRS, necessitating initial acquisitions with the Faint Object Spectrograph, followed by an offset into the GHRS “Large Science Aperture” (LSA). This scheme yields a target-positioning uncertainty in the LSA that potentially could translate into a \( \approx 1 \) Å uncertainty in the absolute wavelength calibration. (However, empirically we find, for example, an offset of only 0.3 Å between the expected and observed wavelengths for the strong interstellar C II absorption component at 1334.5 Å.)

The requirement to use the LSA results in two complications related to limiting geocoronal/airglow contamination. First, a grating tilt was chosen with coverage of 1240–1525 Å that starts safely redward of the very strong geocoronal Lyman-α line. Second, OI 1304 Å airglow cannot be avoided completely as its wavelength is very near to redshifted He\(^+\) Lyman-α for Q0302. Hence, the most useful science observations may be collected only during the spacecraft “nighttime” portions of each HST orbit, and the STScI staff helped ensure that scheduling occurred in a manner to maximize the availability of such dark time.

Based on the earlier FOC estimates of the UV flux, we expected a net count rate from Q0302 significantly lower than the typical GHRS noise background rate. Hence, GHRS science data during the nighttime portions of 16 HST orbits were taken using special noise-rejection commanding known as “FLYLIM”, described in greater detail below. In addition, most of 2 additional HST orbits were devoted to routine “ACCUM” GHRS observations of Q0302 during spacecraft nighttime. Finally, there were brief periods at the beginnings or ends of each HST target visibility period in which the spacecraft was not in
Earth shadow; additional GHRS data were collected in routine ACCUM mode during these brief spacecraft “daytime” periods.

Amongst these various datasets, the FLYLIM/nighttime observations have the greatest statistical precision due to both their longer total integration time, plus reduced noise background, and hence are the focus of most of our analysis. FLYLIM cut the noise background count rate by nearly one-half while rejecting only 7.5% of the integrations. However, as described below our GHRS observations reveal a UV flux for Q0302 in excess of initial FOC expectations (and even somewhat higher than a recent re-calibration of the FOC data by Jakobsen 1996). This higher UV flux interacts with the FLYLIM noise-rejection scheme in a nonlinear manner that necessitates more sophisticated reductions than are standard in the STScI pipeline routines. The additional 2 orbits of ACCUM/nighttime observations are essential to confirming the flux-calibration of the FLYLIM/nighttime observations. The ACCUM/daytime observations are strongly contaminated, especially by geocoronal emission, and therefore not of much direct use for many of the science issues addressed here; nonetheless, they provide useful secondary information on airglow line profiles, and on the distribution of background noise events.

2.1. Calibration of FLYLIM Data

As the proper flux calibration of the FLYLIM/nighttime observations is not automatically handled in the standard STScI pipeline reductions, we discuss here in detail the relevant offline flux corrections. The GHRS background noise (mainly cosmic ray

\[2\] A preliminary analysis using the OI line profile collected from the daytime portions of the orbits suggests that OI contamination is likely to be small in the nighttime observations emphasized here.
induced Cerenkov radiation) is non-Poissonian, arriving predominantly in short bursts of events, and FLYLIM commanding is intended to detect and reject such noise bursts. FLYLIM rejects (onboard the spacecraft) any 0.2s sub-integration in which the total counts accumulated in all 500 GHRS diodes equals or exceeds some specified number of counts; in this case a threshold of 3 counts was selected. This threshold is substantially larger than the count rate expected (per 0.2s) from the QSO itself across all 500 diodes, and thus sub-integrations at or exceeding the threshold of 3 counts are presumed to be noise and rejected. Typical GHRS observing modes spend of order 1/16 of the actual integration time monitoring the noise background and FLYLIM is commanded to reject both on-source sub-integrations (source+background) and background monitoring (background only) sub-integrations with the identical threshold.

There is thus the potential with FLYLIM for subtle background and threshold rejection effects not accounted for in the standard STScI pipeline flux calibration. It is helpful to conceptualize the needed offline flux corrections for FLYLIM data as due to two principal effects, although of course these two are coupled (and hence require a coupled calibration/correction).

First, even if there were no background noise, there would be rare (but expected) positive counting fluctuations from the source (QSO) that would occasionally exceed the FLYLIM threshold, hence causing the rejection of an entire 0.2s sub-integration. Even though rare, such large rejected positive source fluctuations will not be accounted for in the standard pipeline estimation of the source count rate, and this artificially suppresses the standard pipeline inference about the QSO flux. This effect, of course, is wavelength (or diode) dependent, as the QSO count rate itself is wavelength dependent. This effect will be especially important in those regions of the spectrum in which the count-rate is highest, as it is in such wavelength/diode regimes where the largest positive source fluctuations
are most likely. (In the case of Q0302, this will be longward of the He$^+$ break). The flux correction needed to the pipeline-reduced spectrum for this effect is largely a multiplicative one; that is, the actual flux at each wavelength is (approximately) some fixed factor higher than that implied by the standard pipeline reductions, and may be simply estimated as described below.

A second, and perhaps more subtle effect, is that the background count rate may also be misinterpreted with FLYLIM. For concreteness, consider a case in which source+background are being observed, and a background noise event generates 2 counts in a particular 0.2s sub-integration while the source generates 1 count in that same sub-integration. This 0.2s sub-integration on source+background will be rejected by FLYLIM as it attains the threshold value of 3. However, when monitoring only the background (no source), there would not have been a FLYLIM rejection as the 2 count background event itself falls below the rejection threshold. Thus, comparatively lower background rates may lead to FLYLIM rejections when observing source+background than those that lead to FLYLIM rejections when monitoring background only. The result is that for observations taken in FLYLIM mode, the noise background count rate estimated by the standard pipeline reductions (from background-only monitoring data) appears $higher$ than the noise background count rate that is actually allowed through when observing both background+source. This latter effect essentially necessitates a zero-point count-rate (or flux) offset correction to the pipeline reduced data. This zero-point offset is especially important for the low count rate portions of the FLYLIM spectrum (shortward of the He$^+$ break for Q0302), and is corrected for as described below.
2.2. Empirical FLYLIM Flux Correction

With the above simple conceptual model in mind, an empirical flux correction can be made to the standard pipeline reductions of the FLYLIM/nighttime observations, by requiring that the corrected spectrum have both the same overall (low-resolution) spectral energy distribution and the same mean flux as measured directly from the routine ACCUM/nighttime observations. In practice, this is done iteratively. First, an initial estimate of the mean zero-point offset flux correction (corresponding to the second effect discussed in section 2.1) is obtained from the difference between mean fluxes of the routine ACCUM/nighttime and FLYLIM/nighttime pipeline-reduced spectra; the mean fluxes compared here are those shortward of the He$^+$ break in Q0302, where this zero-point offset dominates. Then, with this initial zero-point correction applied, the ratio of mean fluxes between the (now partially corrected) FLYLIM/nighttime spectrum and the routine ACCUM/nighttime spectrum is determined to estimate the (mainly) multiplicative correction corresponding to the first effect discussed in section 2.1; the mean fluxes compared here are those longward of the He$^+$ break, where the first effect dominates. This procedure is iterated until the difference in mean fluxes below the break converges to near zero (to within $\sim 3 \times 10^{-18}$ erg/sec/cm$^2$/Å) and simultaneously the ratio of mean fluxes longwards of the break converges to unity (to within $\sim 0.3\%$). [Note that for these data, in practice it makes no significant difference whether such an empirical correction is done in flux or count/rate units, although the latter is more rigorously consistent.]

The empirically corrected FLYLIM/nighttime spectrum is displayed in figure 1, with the accompanying formal error spectrum. The empirical correction in this case may be thought of as roughly equivalent to a zero-point offset correction of about $2.5 \times 10^{-17}$ erg/sec/cm$^2$/Å coupled with a 30% multiplicative correction to the flux. The error spectrum displayed in figure 1 is appropriate for assessing the statistical significance of
spectral features, but our empirical correction to bring the FLYLIM/nighttime spectrum into agreement with ACCUM/nighttime spectrum also must reflect the zero-point flux uncertainty of the ACCUM/nighttime data. Hence it should also be emphasized that the empirically corrected FLYLIM/nighttime spectrum of figure 1 has inherited a zero-point uncertainty of about $1.1 \times 10^{-17}$ erg/s/cm$^2$/Å (and this zero-point uncertainty is not reflected in the formal error spectrum).

On the other hand, it should also be realized that for most of those discussions below that refer to flux measures—e.g., estimates of the optical depth over broad bands due to He$^+$ absorption—one can use either the entirely routine ACCUM/nighttime spectrum or the empirically corrected FLYLIM/nighttime spectrum of figure 1. Both spectra yield very similar results (including errors, which are dominated over broad bands by the zero-point uncertainty associated with the ACCUM/nighttime observations).

### 2.3. Model FLYLIM Flux Correction

We have also independently confirmed the FLYLIM/nighttime flux corrections by a more detailed quantitative model of the FLYLIM rejection process; in contrast to the empirical correction of section 2.2, the model correction described now does not depend on any recalibration to the ACCUM/nighttime flux. For this more detailed confirmatory model, we assume that the source (QSO) count rate (per 0.2s sub-integration) may be modeled as a Poisson process. For the distribution of GHRS background noise events, a Poissonian model is known to be inadequate so we instead estimate this noise count distribution (i.e., what fraction of noise bursts yield 0,1,2,3,... count events in each 0.2s sub-integration) from the background-only monitoring data collected during each HST science orbit in routine ACCUM mode (i.e., no source and no FLYLIM rejection). These background-only monitoring data are essentially background “spectra” in which all 500
GHRS diodes are read-down in exposures lasting about 7 sec each. We rebin each such background spectrum into bins of ≈14 diodes in width, and count the number of background events yielding 0,1,2,3,... counts in each bin. Effectively, each bin then samples 14-diodes × 7 sec ≈ 100 diode-secs worth of background monitoring data; for the model, we assume that this binning scheme yields a similar distribution of background events as that actually sampled (aboard the spacecraft) in each 0.2s sub-integration across all 500 diodes, as it is also the case that 500-diodes × 0.2s ≈ 100 diode-secs. Finally, we also require that the model account for the empirical constraints that 7.5% of all integrations with FLYLIM implemented were rejected (with the chosen threshold of 3), and that the pipeline-inferred (i.e., uncorrected) background count rate while monitoring background-only (no source) with FLYLIM is 0.0036 cnts/s/diode.

The pipeline-reduced FLYLIM/nighttime spectrum is input to the model as an initial estimate of the actual spectrum, and the model provides a first estimate of the required flux correction (accounting for both the coupled FLYLIM effects described in section 2.1). This partially corrected spectrum is then input again into the model to derive an improved flux correction, and the procedure iterated until convergence. It should be emphasized that the ACCUM/nighttime flux does not in any fashion enter into this model for the flux correction to FLYLIM data.

This model-corrected FLYLIM/nighttime spectrum agrees very well with the empirically-corrected FLYLIM/nighttime spectrum of figure 1. The difference between the mean fluxes for model- and empirically-corrected FLYLIM/nighttime spectra is only 1.0×10^{-17} erg/s/cm^2/Å, and the difference in means shortward of the He^+ break is even smaller at 6.0×10^{-18} erg/s/cm^2/Å. In summary, the excellent flux agreement between empirically-corrected and model-corrected FLYLIM/nighttime spectra on the one hand, plus the agreement between the model-corrected FLYLIM/nighttime spectrum and the
entirely routine (and empirical) ACCUM/nighttime spectrum on the other hand provide strong confirmation that the somewhat subtle offline flux corrections described in this section are properly accounted for in the spectrum of figure 1.

3. Results and Interpretation

3.1. Summary of Absorption Features

The spectrum clearly confirms the main result of Jakobsen et al’s FOC study: the existence of an absorption edge of significant optical depth. It also appears that the absorption is indeed mainly produced by He$^+$ 304 Å line absorption and not by an unrelated low-z HI Lyman limit cloud. First, this is confirmed by the location of the break, which in the GHRS data occurs within about 5.3 Å shortward of the quasar systemic redshift (this may be compared with the ±20Å agreement uncertainty window allowed by the original FOC data). Scaling the arguments presented in Jakobsen et al. (1994), the likelihood of a chance superposition of an HI Lyman limit system (with column exceeding $10^{18} \text{cm}^{-2}$) occurring this close shortward of the QSO systemic redshift is only about 0.3%. Second, in any case our GHRS spectrum does not reveal HI Lyman series absorption, which would have been detectable if a Lyman limit system were responsible for the break.

Most significantly, we find significant coincidence in redshift of helium and hydrogen absorption features— the He$^+$ Lyman-α forest as well as the Gunn-Peterson effect. The portion of the new spectrum of greatest interest is displayed in figures 2a and 2b, overlaid with synthetic spectra, which are models of the absorption expected from the clouds seen in the HI Lyman-α forest absorption. Starting with a Keck spectrum of the quasar (courtesy of A. Songaila, E. Hu and L. L. Cowie), we have fitted Voigt profiles (using VPFIT, Webb 1987) to all the HI line features down to a threshold column density of $10^{12} \text{cm}^{-2}$
(e.g., a central optical depth of 0.05 for \( b = 15 \text{km/s} \)), then used the column densities, Doppler parameters and redshifts of these clouds to predict the \( \text{He}^+ \) absorption, degraded to the resolution of GHRS. (The reason for this roundabout modeling, rather than simply multiplying the observed HI transmission by a constant factor [as in e.g. Songaila et al. 1995] is to allow us to model either turbulent or thermal cases, depending for each argument on whether maximum or minimum helium absorption is appropriate).

Note that several \( \text{He}^+ \) absorption features correlate in detail with features predicted from HI; the main edge is itself one example of such a feature, caused by an identifiable complex of HI clouds. This edge is centered at \( z = 3.268 \), which is less than the systemic redshift of the quasar but matches that of the clouds. This is expected since the ionizing radiation from the quasar reduces absorption from the diffuse foreground gas more than from saturated clouds (Zheng and Davidsen 1995, Giroux et al. 1995) The traditional redshift \( z = 3.285 \) of Q0302, which would place the edge at 1302\(^\text{Å} \) instead of the observed 1296.4\(^\text{Å} \) is probably quite close to the “true” cosmic or systemic redshift of the quasar, as nearly the same redshift is derived from both Lyman-\( \alpha \) and from other, narrower lines including the [OIII] 5007 emission line; see Espey et al. 1996. The coincidence (to within \( \sim \) 1 resolution element) of the three reddest absorption features with the HI predictions—especially the main edge—suggests that the absorption indeed arises from high redshift helium even though the edge is not at precisely the quasar systemic redshift.

Beyond the main edge, a significant “shelf” of flux (mean optical depth about 0.8, level \( 11.8 \pm 1.4 \times 10^{-17} \text{ erg/sec/cm}^2/\text{Å} \)) extends for about another 10\(^\text{Å} \), to about 1283\(^\text{Å} \) (20\(^\text{Å} \) shortwards of the “expected” edge). We attribute this entire shelf to the fact that in this region more of the \( \text{He}^+ \) is doubly ionized due to the hard radiation from the quasar (the “proximity effect”), greatly reducing absorption from diffuse gas.

The second edge at 1283\(^\text{Å} \) coincides with the highest HI column cloud measured,
log $N(HI) = 15.8$, which may even be optically thick in the He$^+$ Lyman limit. At shorter wavelengths the flux decreases further beyond the second edge. For broad comparison with the results of other studies, we note that here the total He$^+$ optical depth (which includes both cloud and diffuse gas contributions) is $\tau_{\text{total}} \approx 2.0$, if we compare the mean flux averaged over the 40Å region shortward of the “shelf” to a similar region longward of the He$^+$ break; the 95% confidence range on $\tau_{\text{total}}$ is 1.5 to 3.0, compared with the shelf average of 0.8. Since the contribution from highly saturated clouds is little affected by the proximity effect, the change or extra absorption, an optical depth of the order of unity, is probably caused by unsaturated, redshift-space-filling, diffuse intergalactic gas. In this sense we confirm quantitatively the conclusions of Jakobsen et al. (1994).

There is some flux detected even near the very bluest portions of the spectrum of figure 1. For example, in a 20 Å bin between 1240 and 1260 Å the mean flux is $5.0 \times 10^{-17}$ erg/s/cm$^2$/Å with a formal (photon counting) error of $\pm 0.6 \times 10^{-17}$ erg/s/cm$^2$/Å (and the zero-point offset error of $1.1 \times 10^{-17}$ erg/s/cm$^2$/Å discussed in section 2.2). This is at least indicative of a flux recovery towards lower redshift: for example, the mean flux in the 1240–1260 Å bin is marginally larger by about $2.9\sigma$ than that ($2.8 \times 10^{-17}$ erg/s/cm$^2$/Å with similar errors) in a redder adjacent bin extending over 1260–1280 Å. Note that the zero-point offset error is not relevant when comparing the difference in flux between these adjacent bins. Such a flux recovery is expected in many models and is certainly expected from the results of Davidsen et al.

The predicted spectra in figure 2 depend on the adopted column densities and Doppler parameters of the He$^+$. The models displayed in figure 2a simply assume two constant ratios for all the clouds, $\eta \equiv N(He^+)/N(HI) = 20$ (corresponding to a spectral slope $\alpha = 1.8$, the typical value observed in low redshift quasars and probably appropriate for the unabsorbed ionizing spectrum in the near-quasar zone here), and $\eta = 100$ (corresponding
to our limit $\alpha \geq 3$ derived below for the slope far from the quasar). Figure 2b shows the result for maximal absorption from an extremely soft spectrum, in order to demonstrate that the observed HI clouds alone cannot for any spectrum explain the absorption in the Lyman-\(\alpha\) voids. All the models shown in figure 2 have $\xi \equiv b_{He}/b_{H} = 1$ for all components (pure turbulent broadening, giving the maximal helium/hydrogen optical depth). The absorption is quite sensitive to $\xi$ but not to $\eta$ as the helium absorption by clouds is highly saturated; even very large values of $\eta$ do not yield significantly more absorption than the models shown if $\xi = 0.5$. Due to variations in $\xi$ a precise agreement of the simple model with the data is not expected even where the spectrum is uniform.

In the following subsections we will develop several separate quantitative lines of argument based on different features of the spectrum. In the “shelf” region of the spectrum the absorption is, within our errors (including the uncertainty in the intrinsic quasar spectrum), accounted for entirely by the gas in clouds, provided $b_{He} \approx b_{H}$ for at least some of the clouds. Diffuse absorption of large optical depth in this region is however not consistent with the data, and this fact can be used together with the known ionizing spectrum of the quasar to set an upper limit on the diffuse gas density near the quasar. Knowledge of the spectrum yields broad constraints on the absolute value of the helium abundance. Shortwards of 1283 Å, the forest clouds are not sufficient to explain all of the absorption; indeed there is significant helium opacity even in the well-known “void” in the HI forest (Dobrzycki & Bechtold 1991) from which we derive a lower limit on $\eta$ and and a constraint on the intergalactic ionizing spectrum far from the quasar, which roughly agrees with the absolute He$^+$ ionizing flux estimated from the proximity effect. In spite of the soft spectrum there is residual flux throughout the spectrum, which gives a separate upper limit on the diffuse gas density far from the quasar and also indicates that it is likely that the intergalactic helium is mostly doubly ionized by this epoch.
3.2. Conditions Near the Quasar

In the region near the quasar, the He\(^+\)-ionizing flux can be estimated directly from the observed quasar flux, with several caveats. If there is dust absorption along the line of sight, the true continuum level is everywhere greater than observed, and the slope of the spectrum is shallower; in addition, the accumulated Lyman limit absorption of foreground HI clouds reduces the observed flux shortwards of 912 Å in the rest frame (e.g., Vogel and Reimers 1995); and the quasar flux may vary on a timescale long compared with observational baseline but short compared to relevant ionization and recombination rates. These effects lead to uncalibrated uncertainties which can only be removed by additional observations; variability and absorption alter the estimate of the local ionizing flux, leading to changes in the proximity arguments, while the unknown intrinsic continuum slope leads to an uncertainty the continuum flux and hence in all our estimated optical depths. Our approach here is to “parametrize our ignorance” in correction factors for these effects. The factors can be constrained using other data, for example spectrophotometry of the quasar over a larger wavelength range (extending longwards of 912 Å in the rest frame), or statistical surveys of other objects.

We assume that the flux at the He\(^+\) ionizing continuum edge \(\nu_i\) (\(\lambda_i = 228\) Å rest) would if unabsorbed be close to the observed flux longwards of 304 Å. (The modest equivalent width inferred for the 304 Å emission line seems to indicate that the helium-ionizing flux from Q0302 is largely escaping, and in the 228–304Å region the spectrum is likely to be fairly flat.) We allow for the possibility of other sources of absorption along the line of sight, such as an accumulation of Lyman continuum absorption, reducing the flux by a total factor \(R^{-1}\); the flux at the continuum edge if unabsorbed is then \(f_\lambda \approx 2.6 \times 10^{-16} R\) erg cm\(^{-2}\) s\(^{-1}\) Å\(^{-1}\), (or \(f_\nu \approx 8 \times 10^{-30} R\) erg cm\(^{-2}\) s\(^{-1}\) Hz\(^{-1}\)). We assume an intrinsic power law spectral energy distribution \(f_\nu \equiv f_\lambda \nu^{-\alpha}\). Zheng and Davidsen
(1995) estimate that the intrinsic $\alpha \approx 1.5$, although $\alpha \approx 2.4$ has been measured directly and $\alpha \approx 1.8$ appears to be typical of nearby samples. For some arguments it is appropriate to normalize to the observed flux at HI Lyman-$\alpha$, in which case it is appropriate to use a different quantity, the multiplicative difference in the foreground absorption between the HI and He$^+$ Lyman-$\alpha$, $R_{304/1216} \approx 4^{2.5-\alpha}$. For the plausible range of $\alpha$, $R_{304/1216}$ is likely in the range between 1 and 4. Similarly for some arguments it is appropriate to use the ratio at the continuum edges, $R_{228/912}$.

At a point along the line of sight at redshift $z_Q - \delta z$, the quasar spectral density is (Bajtlick et al. 1988)

$$F_\nu = 4f_\nu \delta z^{-2}(1 + z)^{5/2}[(1 + z)^{1/2} - 1]^2$$

if $\Omega = 1$, and

$$F_\nu = f_\nu \delta z^{-2}z^2[1 + (z/2)]^{1/2}(1 + z)^3$$

if $\Omega = 0$, independent of $H_0$; for the present case $z_Q = 3.285$, we find $(F_\nu/f_\nu)\delta z^2 = 6.5 \times 10^3$ and $6.3 \times 10^3$ respectively. Expressing the offset $\delta z$ from the quasar systemic He$^+$ Lyman-$\alpha$ redshift in terms of observed wavelength offset $\delta \lambda = 304\AA \delta z$ from the quasar He$^+$ Lyman-$\alpha$, $304\AA (1 + z_Q) = 1302\AA$, we estimate the spectral flux

$$F_\nu = 1.2 \times 10^{-23}(\delta \lambda/20\AA)^{-2}R \text{ erg cm}^{-2} \text{ s}^{-1} \text{Hz}^{-1},$$

the ionizing photon flux

$$F_\gamma \equiv \int_{\nu_i}^{\infty} d\nu (F_\nu/h\nu) \approx 1.9 \times 10^{4}\alpha^{-1}(\delta \lambda/20\AA)^{-2}R \text{ cm}^{-2} \text{ sec}^{-1}$$

and the He$^+$ ionization rate (e.g., Osterbrock 1989)

$$\Gamma_{He^+} \equiv \int_{\nu_i}^{\infty} d\nu (F_\nu \sigma_\nu/h\nu) \approx 3.0 \times 10^{-14}(\alpha + 3)^{-1}(\delta \lambda/20\AA)^{-2}R \text{ sec}^{-1},$$

where the photoelectric cross section of He$^+$, $\sigma_\nu = 1.6 \times 10^{-18}\nu^3 \text{ cm}^2$. 

3.3. Quasar Lifetime and Ionizing Background from the Proximity Effect

A quasar can doubly ionize all the helium out to a distance of
\[ r = \left[ \frac{\delta z}{1 + z} \right] \frac{c}{H(z)} \]
if the photon flux \( F_{\gamma} \) is maintained for a characteristic time
\[ t_Q = r n_{He} / 3 F_{\gamma} \], where for cosmic abundance (0.08 by number) the density of helium atoms is related to the density parameter of gas by
\[ n_{He} = 9 \times 10^{-7} \Omega_g h^2 (1 + z)^3 \text{cm}^{-3} \]. For \( \Omega = 1 \) we estimate a time for double-ionizing to offset \( \delta \lambda \),
\[ t_Q \geq 0.6 \times 10^7 h^{-1} \text{yr} \alpha R^{-1} (\delta \lambda / 20 \text{Å})^3 (\Omega_g h^2 / 10^{-2}), \]
and about twice this for \( \Omega = 0 \). It is therefore plausible for the helium ionization zone to extend about 20 Å shortwards of the quasar redshift if the lifetime of this quasar is of the order of the characteristic Eddington/Salpeter evolution time for accretion, \( 4 \times 10^8 \text{yr} \) for typical radiative efficiency \( \epsilon \equiv E_{\text{total}}/Mc^2 \approx 10\% \), even if the gas begins as mostly singly ionized.

If we take \( \delta \lambda \approx 20 \text{Å} \) as the point where the quasar ionizing flux is equal to the ionizing background, the ionizing spectrum has a specific intensity
\[ J_{228} \approx 10^{-24} R \text{ erg cm}^{-2} \text{ s}^{-1} \text{Hz}^{-1} \text{sr}^{-1}, \] implying a soft spectrum, with ratio of hydrogen to helium intergalactic ionizing fluxes \( S \equiv J_{912} / J_{228} \approx 10^3 R^{-1} J_{912,-21}. \)

The predictions based on observed quasar populations are quite sensitive to the assumed typical value of \( \alpha \) and to models of the absorption. Haardt and Madau (1996) predict \( \eta \approx 40 \) at this redshift, although the prediction is likely to increase as \( \alpha \) is revised (from 1.5 say to 1.8; P. Madau, private communication). The flux here corresponds to

\[ n_e \alpha_{He^+} \approx 8 \times 10^{-17} \Omega_g h^2 (\rho/\bar{\rho}) \text{sec}^{-1} \] which is slower than the Hubble rate \( H \approx 3 \times 10^{-17} h \text{sec}^{-1} \) for \( \Omega_g \approx 0.01 \). If much of the gas is in density concentrations, recombinations can be important, requiring a longer quasar lifetime.

\[ \text{We ignore helium recombinations for this argument. In gas with density contrast } \rho/\bar{\rho}, \text{ the recombination rate is } n_e \alpha_{He^+} \approx 8 \times 10^{-17} \Omega_g h^2 (\rho/\bar{\rho}) \text{sec}^{-1} \text{ which is slower than the Hubble rate } H \approx 3 \times 10^{-17} h \text{sec}^{-1} \text{ for } \Omega_g \approx 0.01. \]
\[ \eta \approx 1.7S \approx 200 \text{ for } R = 4 \text{ and } J_{912,-21} = 0.5; \text{ within the uncertainties of both arguments, we consider the agreement satisfactory, almost remarkable since it is derived from just one quasar. (Note the independent limit derived below, } \eta \geq 100, \text{ without reference to the proximity effect.)} \]

### 3.4. Diffuse Gas Near the Quasar

The lack of diffuse absorption leads to an upper limit on the diffuse gas density in the \( He^{++} \) bubble, since the ionizing flux from the quasar is known. Continuous absorption of optical depth \( \tau_{GP} \) is produced by diffuse \( He^{+} \) (which in this context means atoms producing unsaturated absorption at redshift \( z \)), where the density is given by the standard Gunn-Peterson formula (Peebles 1993)

\[
n_{He^+} = \frac{(8\pi/3)\tau_{GP} [\lambda_{\alpha}(1+z_{\alpha})]^{-3} H(z) \Lambda^{-1}_{\alpha}}{\Omega g h^2},
\]

where the transition rate for helium Lyman-\( \alpha \), \( \Lambda_{\alpha}(He) = 16 \Lambda_{\alpha}(H) = 1.0 \times 10^{10} \text{ sec}^{-1} \). At \( z = 3.285 \) this becomes \( n_{He^+} = 0.9 \times 10^{-9} h \tau_{GP} cm^{-3} \) or equivalently

\[
\Omega_g h^2 = 1.7 \times 10^{-5} h \tau_{GP} (n_{He^+}/n_{He})^{-1}.
\]

The fraction of helium in \( He^+ \) is given by

\[
n_{He^+}/n_{He} = n_e \alpha_{He}/\Gamma_{He^+} \approx 3.6 \times 10^{-2} (\rho/\bar{\rho}) \Omega_g h^2 (\delta \lambda/20 \text{ Å})^{-2} (\alpha + 3) R^{-1/2} T^{-1/4},
\]

where the density contrast of the material is \( (\rho/\bar{\rho}) \) and the recombination coefficient is given near \( T_4 \equiv T/10^4 K = 1 \) by (Spitzer 1978)

\[
\alpha_{He^+} = 3.4 \times 10^{-13} Z^2 T_4^{-1/2} cm^3 \text{ sec}^{-1}.
\]

This results in a limit on the diffuse gas density in the bulk of velocity space (and hence, the bulk of the intergalactic spatial volume),

\[
\Omega_g h^2 = 2.1 \times 10^{-2} \tau_{GP}^{1/2} (\rho/\bar{\rho})^{-1/2} (\delta \lambda/20 \text{ Å})^{-1} (\alpha + 3)^{-1/2} R^{1/2} T_4^{1/4} h^{1/2}.
\]
where $\tau_{GP}$ is the limit on the continuous opacity at the offset $\delta \lambda$. We conservatively estimate from our data $\tau_{GP} \leq 1.35$ at $\approx 1285\text{Å}$ (a 95% confidence limit, conservatively neglecting any discrete cloud opacity contribution), leading to an upper limit on diffuse intergalactic gas of

$$\Omega_g \leq 0.019 R^{1/2}(\alpha/1.5)^{-1/2}(h/0.7)^{1/2} ;$$

tied to the observed quasar flux.

This limit is interesting since it is of the same order as the baryon density required by Standard Big Bang Nucleosynthesis (Walker et al 1991, Smith et al 1993, Copi et al 1995, Sarkar 1996, Hogan 1997). Current estimates of the total range from $\Omega_b \approx 0.01(h/0.7)^{-2}$ (e.g. Rugers & Hogan 1996) to $\Omega_b \approx 0.05(h/0.7)^{-2}$ (e.g. Tytler et al. 1996). Realistic CDM models predict that most of the baryons should be concentrated in clouds by this epoch, so our result accords with expectations even for large baryon density (Croft et al. 1997).

### 3.5. Helium Abundance

Since both hydrogen and helium are mostly ionized, a precise abundance measurement is not possible from absorption which only studies a small fraction of the material. However, because of the unique information on helium at high redshift (before the bulk of baryonic material had even formed into stars), it is interesting to ask how our data quantitatively constrains the abundance, even if imprecisely.

An absolute helium abundance can be estimated from HI and He$^+$ Lyman-\(\alpha\) absorption but only if: (1) the helium abundance is uniform; (2) He$^+$ and HI are in ionization equilibrium; (3) we know the shape of the ionizing spectrum; (4) absorption is unsaturated, so column densities of absorbing species can measured. The total columns of He$^+$ and HI are then both proportional to the same line integral $\int d\ell n_c^2$ with coefficients depending on
the abundance and the ionizing spectrum. (Note that even this statement applies only to the redshift integrated column densities; there is only agreement at particular redshift in the case of negligible thermal contributions to the atomic velocities. Note also that in principle, another test is possible: in regions where the ionizing spectrum is uniform, even if it is not known, constraints on variations in $\eta$ translate into constraints on the spatial variations of $Y$.)

These conditions are certainly not met here in detail, but the data also do not allow arbitrary variations in abundance. For example, ionization equilibrium relates the value of the (redshift-) integrated column density ratio $\eta$ to the absolute abundance of helium,

$$\frac{Y}{0.24} \approx \frac{\eta}{1.7S_{228/912}}$$

provided we know the ratio of ionizing fluxes $S_{228/912}$. We can explore the range of allowed $\eta$ by our family of models based on the HI absorption, and the value of $S_{228/912}$ is constrained in the region dominated by quasar radiation, subject to the uncertainties discussed above. Using the above estimates of quasar fluxes, $S_{228/912} \approx 28R_{228/912}^{-1}$, yielding

$$\frac{Y}{0.24} \approx 0.84 \left( \frac{\eta}{10} \right) \left( \frac{R_{228/912}}{4} \right)^{-1}$$

The best guesses from the current data are that $10 \leq \eta \leq 20$ and $2 \leq R_{228/912} \leq 4$, so that $Y$ must lie within a factor of a few of the standard big bang prediction. Although the constraints on $\eta$ and $R_{228/912}$ will both improve (the first from better signal to noise, the second from better spectrophotometry), it is still unlikely that a reliable estimate can be made much more precise than this because of the many assumptions required. The most interesting new result here is the approximate concordance with Big Bang predictions at a large distance and an early epoch, and over a large volume of space.
3.6. Diffuse Gas in the HI Lyman-α “Voids”: Lower Limit

Assuming He$^+$ is the dominant species leads to a conservative lower limit on the density in absorbing gas,

$$\Omega_g h^2 = 1.65 \times 10^{-5} h \tau_{GP} (n(He^+)/n(He))^{-1} [(1 + z)/4.285]^{-3/2}.$$ 

In the HI Lyman-α void redshift range (especially near $\lambda_{HI} \approx 4 \times 1266\text{Å}$), the optical depth of He$^+$ absorption required by our data, after allowing for the absorption from identified clouds (which in the void is almost independent of $\eta$), is still $\tau_{GP} > 1.3$ (95% confidence), requiring a diffuse density,

$$\Omega_g > 3 \times 10^{-5} (h/0.7)^{-1}.$$ 

This is essentially the same as derived by Jakobsen et al., except that we can now rule out the possibility of producing this opacity with HI clouds down to the detectability threshold $\tau_{GP} \leq 0.05$ in HI absorption $N(HI) = 10^{12} \text{cm}^{-2}$. The higher resolution here shows that the helium opacity appears even between the most rarefied detected HI clouds. Of course for $\eta \geq 100$, much of the He$^+$ absorption could still be from saturated lines not yet resolved in our data.

In current models, absorption is produced in components of lower column density but these components are produced by “clouds” which are indistinguishable from (are really just parts of) the diffuse, space-filling protogalactic medium (Cen et al. 1994; Hernquist et al. 1996; Croft et al 1997; Zhang et al 1997; Bi and Davidsen 1997). The opacity required by our data is roughly in accord with these models. We will argue below that it is implausible to evacuate space with very high efficiency so that the bulk of the helium must be doubly ionized, and even then the constraints on the spectrum impose an interesting upper limit on the density.
3.7. Ionizing Spectrum Far from the Quasar

The large ratio of helium to hydrogen optical depths in the void indicates a soft ionizing spectrum far from the quasar. If the HI and He$^+$ are both optically thin, the ratio of optical depths can be used to constrain $\eta$ directly via $\tau_{GP}(He^+)/\tau_{GP}(HI) = \eta/4$ (see Miralda-Escudé 1993). In ionization equilibrium $\eta$ is related to the spectral softness parameter $S$ (e.g., Giroux et al. 1995),

$$\eta = \frac{\alpha_{He^+}}{\alpha_H} \frac{\Gamma_H}{\Gamma_{He^+}} \frac{n_{He}}{n_H} = 1.7S$$

where $\alpha$ and $\Gamma$ are the recombination and ionization rates respectively for the two species, and we have assumed the cosmic abundance 0.08 and a temperature $T_4 = 2$. In the Lyman-Î± void redshift range (i.e., near $\lambda_{HI} \approx 4 \times 1266$ Å), the average optical depth of diffuse HI absorption allowed is at most 0.05. (Since uniform HI absorption could have escaped detection at this level, this limit of 0.05 assumes that there are some variations in $\tau(z)$, as expected from simulations.) The optical depth of He$^+$ is at least 1.3, requiring $\eta \geq 100$, $S \geq 63$, and hence an ionizing spectrum of $\alpha > 3.0$. (This limit becomes stronger if the helium absorption is not from uniform gas or comes from saturated absorbers.) This is consistent with only soft radiation having reached this material as expected if He$^+$ absorption is still strongly modifying the emitted spectra of quasars. The evidence for a soft spectrum is consistent with that inferred from SiIV/CIV ratios (Songaila and Cowie 1996, Savaglio et al 1997), especially considering the sensitivity of these estimates to details of the spectrum and relative metallicity (Giroux and Shull 1997).

We cannot (without a model of the gas distribution) derive from this data an upper limit to $\eta$ far from the quasar: if we assume only the minimal (thermal) absorption from the clouds, even $\eta \approx 5000$ does not yield excessive absorption from the clouds.
3.8. Upper Limit on $z$–filling Gas from the HI voids

Although we know that there is diffuse gas between the forest clouds, we also know there cannot be too much of it or else there would be no light getting through, whereas we have an upper limit of $\tau_{GP} \leq 3$ on the mean optical depth. Since we also know the ionizing spectrum is soft, we can deduce a limit on the IGM density, tied not to the ionizing flux from the quasar (as we did above) but to the cosmic ionizing flux at the HI Lyman edge, $J_{912,-21}$ (in units of $10^{-21}$ erg cm$^{-2}$ s$^{-1}$ sr$^{-1}$ Hz$^{-1}$), which has other observational constraints such as the HI clouds proximity effect (e.g. Madau and Meiksin 1994):

$$\Omega_g = 0.07 \tau_{GP}^{0.5} \left( \frac{1 + z}{4.3} \right)^{-2.25} \eta^{-0.5} J_{912,-21}^{0.5},$$

which yields

$$\Omega_g = 0.018 (\tau_{GP}/3)^{0.5} (h/0.7)^{-1.5} (\eta/100)^{-0.5} (J_{912,-21}/0.5)^{0.5}.$$  

We thus get a conservative limit $\Omega_g = 0.018$ by taking two 95% limits, one to constrain $\eta \geq 100$ (from the lower limit $\tau > 1.3$ in the void, above) and one from the upper limit on the mean total $\tau < 3$ everywhere, and using typical estimates $J_{912,-21} \approx 0.5$ (Haardt and Madau 1996, Giallongo et al. 1996, but see Cooke et al. 1996). For a better estimate we should allow for the absorption we know is coming from the HI clouds; from our near-quasar analysis, we guess that $\tau \approx 1$ from identified clouds, allowing only $1.3 \leq \tau \leq 2$ more from $z$–filling gas. A reasonable guess for the diffuse gas density is then $\Omega_g \approx 0.01(h/0.7)^{-1.5}$, or even less if $\eta$ is larger than 100 as suggested by the proximity effect. The limit is significantly better than that from studies from the HI Gunn-Peterson effect, which yield limits $\Omega_g \leq 0.2 J_{912,-21}$ at $z = 3$ (Giallongo et al. 1992), and comparable to the (more model-dependent) limit $\Omega_g \leq 0.01$ at $z = 4.3$ (Giallongo et al. 1994).
3.9. Ionization History

Although it is possible that He\(^+\) is the dominant species in the intergalactic gas, the upper limit of 3 on the mean optical depth would allow in this case at most a density of \(\Omega_g \leq 7 \times 10^{-5}\) in diffuse gas—a number so low that it appears more likely that the ionization bubble around Q0302 is a “proximity effect”—that is, double ionized helium is already predominant everywhere, and we are just seeing the region nearest the quasar with an even higher ionization. The main features of our observed spectrum are indeed predicted by models of the proximity effect in which a significant contribution to the mean He\(^+\) opacity comes from the forest clouds (Giroux et al. 1995). [Note that HS 1700+64 shows no such proximity effect (Davidsen et al. 1996), which is most easily explained if the absorption somewhat later at \(z = 2.72\) is everywhere dominated by saturated lines in clouds.] The comoving radius today of the observed He\(^{++}\) bubble is \(H_0 r_0 = [(\delta \lambda / 20 \text{Å})] \times 4600\text{km/sec}\) and 2200 km/sec respectively for open and flat cosmologies. If the Q0302 bubble is typical, the protogalactic gas has entropy and ionization-state inhomogeneities of the order of unity on this scale. The scale of the bubble is not negligible compared to the scale over which the “recovery” appears to occur in our spectrum, so it is not clear whether we are seeing a cosmic trend or merely the history of radiation percolation (to the redshift of the “recovery”) along this line of sight. There is thus strong motivation for obtaining a high quality spectrum of Q0302 that extends to lower redshifts than probed by our GHRS data.

4. Summary

The absorption observed here is broadly consistent with the expectations of hierarchical models of structure formation and with conservative models of cosmic ionization. It is clear that this type of data will be an important constraint on models and their parameters, especially concerning the most diffuse gas filling the bulk of spatial volume.
The main new conclusions from the current data are: 1. The He$^+$ Lyman-\(\alpha\) forest is detected; 2. The “diffuse” (redshift-space-filling) medium is also detected, and must have a low density (\(\Omega \leq 0.01(h/0.7)^{-3/2}\)) consistent with standard primordial nucleosynthesis and models of early gas collapse into protogalaxies; 3. The intergalactic ionizing spectrum is soft (\(\eta \geq 100\)), although the intergalactic helium is probably mostly doubly ionized by \(z = 3.3\); 4. The helium abundance is within a factor of a few of standard Big Bang predictions, over a large volume of space at high redshift.

There is clearly a strong motivation to get a spectrum of other quasars of comparable quality at the same redshift; if we are to draw universal generic conclusions about cosmic ionization history, it would be prudent both to extend our results to lower redshift in Q0302, and to have more than a single line of sight to check assumptions about intrinsic quasar properties and uniformity on different sightlines. In spite of the persuasive checks of the GHRS calibration, it would also be good to verify that the zero level is correct in order to strengthen our limit on the diffuse gas density. These programs are now underway with HST/STIS.

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Fig. 1.— HST/GHRS spectrum and formal error spectrum (latter appropriate for assessing the significance of spectral features), both displayed at the instrumental resolution of 0.6Å, using an iterative empirical flux correction for the nighttime FLYLIM observations. The correction scheme leaves a residual 1σ uncertainty in the zero level of $1.1 \times 10^{-17}\text{erg cm}^{-2}\text{s}^{-1}\text{Å}^{-1}$.

Fig. 2.— A portion of the HST spectrum overlaid with a model spectrum predicted on the basis of the model distribution of HI derived from a Keck spectrum of the HI Lyman-α forest. The quasar emission spectrum is fitted with a flat continuum with flux $2.6 \times 10^{-16}\text{erg cm}^{-2}\text{s}^{-1}\text{Å}^{-1}$, plus an He$^+$ emission line (centered at 1303Å, FWHM 4000 km/sec, and equivalent width of 5Å). Ticks indicate the fitted HI velocity components from the Keck spectrum. Doppler parameters and column densities from the fit were used to predict the He$^+$ absorption spectrum at the GHRS resolution. Two predictions are shown in figure 2a (upper panel), dotted and dot-dash curves corresponding to $\eta = 20$ and 100 respectively, both models assuming pure turbulent broadening, $b_{He^+} = b_{HI}$; figure 2b (lower panel) shows $\eta = 500$ (and $\eta = 100$ again for comparison). Note: (1) the HST and Keck spectra appear to show corresponding absorption features near the He$^+$ edge; (2) $\eta = 20$ is probably sufficient to explain the absorption features near the quasar entirely with clouds; (3) a large ($\tau_{GP} \geq 1.35$) Gunn-Peterson optical depth is only allowed outside the proximity of the quasar, below about 1283Å; (4) there is significant He$^+$ opacity ($\tau_{GP} > 1.3$) even at the redshift of the conspicuous HI Lyman-α forest void near 1266Å; (5) there is significant nonzero flux even far from the quasar.
