CONSTRANTS ON QUASAR LIFETIMES AND BEAMING FROM THE He II Lyα FOREST

STEVEN R. FURLANETTO\textsuperscript{1} AND ADAM LIDZ\textsuperscript{2}
\textsuperscript{1} Department of Physics & Astronomy, University of California Los Angeles, Los Angeles, CA 90095, USA; sfurlane@astro.ucla.edu
\textsuperscript{2} Department of Physics & Astronomy, University of Pennsylvania, Philadelphia, PA 19104, USA
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ABSTRACT

We show that comparisons of He II Lyα forest lines of sight to nearby quasar populations can strongly constrain the lifetimes and emission geometry of quasars. By comparing the He II and H I Lyα forests along a particular line of sight, one can trace fluctuations in the hardness of the radiation field (which are driven by fluctuations in the He II ionization rate). Because this high-energy background is highly variable—thanks to the rarity of the bright quasars that dominate it and the relatively short attenuation lengths of these photons—it is straightforward to associate features in the radiation field with their source quasars. Here we quantify how finite lifetimes and beamed emission geometries affect these expectations. Finite lifetimes induce a time delay that displaces the observed radiation peak relative to the quasar. For beamed emission, geometry dictates that sources invisible to the observer can still create a peak in the radiation field. We show that both these models produce substantial populations of “bare” peaks (without an associated quasar) for reasonable parameter values (lifetimes $\sim 10^6$–$10^8$ yr and beaming angles $\lesssim 90^\circ$). A comparison to existing quasar surveys along two He II Lyα forest lines of sight rules out isotropic emission and infinite lifetime at high confidence; they can be accommodated either by moderate beaming or lifetimes $\sim 10^7$–$10^8$ yr. We also show that the distribution of radial displacements between peaks and their quasars can unambiguously distinguish these two models, although larger statistical samples are needed.

Key words: cosmology: theory – intergalactic medium – quasars: absorption lines – quasars: general

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1. INTRODUCTION

Quasar spectra provide powerful probes of both the source’s properties and the intergalactic medium (IGM). One particularly useful aspect is the so-called proximity effect, which describes the highly ionized zone surrounding each bright quasar. Measuring the transition from this zone to the more uniform ionizing background characteristic of the average IGM provides an estimate of the magnitude of that background as well as source properties such as the quasar luminosity, lifetime, variability, and emission geometry.

The classical proximity effect test uses the zone along the line of sight to a bright quasar by measuring the H I Lyα forest. The increased radiation background causes excess transmission in the forest near to the quasar, which one can model to extract the ionization rate of H I, $\Gamma_{\text{HI}}$ (Bajtlik et al. 1988; Scott et al. 2000). However, the H I proximity zone typically only spans a few Mpc, within the overdense neighborhood of the quasar’s massive host galaxy, and it is difficult to disentangle the intrinsic transmission bias of this region (Faucher-Giguère et al. 2008).

Another flavor, the so-called transverse proximity effect, can be more powerful. Here, we measure the impact of radiation from a foreground quasar on a different Lyα forest skewer: as the line of sight passes the foreground quasar, the forest should show an enhanced ionizing background. However, if the foreground quasar’s light is beamed—toward the observer, in this case—or if the quasar has a short enough lifetime, its radiation may not even intersect the Lyα forest skewer at all, or at least it may not strike it at the point of closest approach. Thus, the pattern of enhancements near foreground quasars should reveal information about the lifetime, beaming, and variability of quasars (Crotts 1989; Moller & Kjaergaard 1992; Adelberger 2004; Schirber et al. 2004; Crotf 2004).\textsuperscript{3}

With the H I Lyα forest, one still only expects to see an enhancement in the biased environment very close to the quasar (within $\lesssim 3$ Mpc; Faucher-Giguère et al. 2008; Hennawi et al. 2006). Such close pairs of quasars are rare, even in modern data sets. Only recently have large surveys and more careful analysis led to the detection of the transverse effect: Gonçalves et al. (2008) used higher-ionization metal line ratios to measure lifetimes $\sim 3 \times 10^7$ yr with no evidence for anisotropic emission, while Kirkman & Tytler (2008) searched 130 quasar pairs, with separations $\lesssim 3$ Mpc, and found no increased transmission in the foreground but decreased transmission in the background, which they explain by appealing to rapid ($\sim 10^9$ yr) variability.

However, the He II Lyα forest offers a better measurement of the transverse proximity effect. It has two important advantages. First, the He II ionization rate (for which we will use $\Gamma$ as a shorthand for $\Gamma_{\text{HeII}}$) is much more variable than $\Gamma_{\text{HI}}$ (Fardal et al. 1998; Maselli & Ferrara 2005; Bolton et al. 2006; Meiksin 2009; Furlanetto 2009a, 2009b). Each quasar dominates the local high-energy radiation field in a much larger region—tens of comoving Mpc—than it does for H I, so the signature is much easier to identify. Second, we can compare the He II and H I forests in order to measure the hardness of the ionizing background. This eliminates the dependence on density (and temperature), which affect both the He II and H I fractions in the same way, and removes any ambiguity due to the quasar environment (Faucher-Giguère et al. 2008). To the extent that the H I-ionizing background is uniform, we can also therefore cleanly measure the He II-ionizing background.

These two factors make the detection and extraction of physical quantities much simpler with the He II forest. Indeed, the transverse proximity effect has already been detected along two different lines of sight (Jakobsen et al. 2003; Worseck & Wisotzki 2006; Worseck et al. 2007), even with low signal-to-noise spectra.
In this paper we will show, using a pair of simple toy models, that the transverse proximity effect, applied to the He\textsc{ii} forest, provides great discriminating power between quasar models with finite lifetimes and/or anisotropic emission. Although the models could also be applied to the standard H\textsc{i} transverse proximity effect, the close quasar pairs required to detect it, and the biased environment of each quasar, makes its interpretation much more difficult (as the recent surveys attest). We therefore focus exclusively on the He\textsc{ii} case here. The simple models we use would require much more sophistication to be applied to the H\textsc{i} case. We will also show that, in the case of finite lifetimes, pairs at $\gtrsim 10$ Mpc offer the best constraints, making the H\textsc{i} proximity effect intrinsically less useful.

This paper is organized as follows. In Sections 2 and 3, we use toy models of quasars with finite lifetimes and beaming to compute the fraction of peaks in the radiation field that have nearby observable quasars. In Section 4, we show that the angular distribution of the peak–quasar associations can distinguish these two sets of models. Finally, we compare to existing observations in Section 5 and conclude in Section 6.

All distances are quoted in proper units unless otherwise specified.

2. QUASARS AND RADIATION PEAKS: FINITE LIFETIMES

Here we will use toy models and simple statistics to illustrate the power of the He\textsc{ii} transverse proximity effect. Our basic approach is to measure the fraction of peaks in the radiation field identified along an Ly\textsc{a} forest skewer and in which only peaks with $\sigma > 8$ are identified. In (a), the (upper) thin curves take $r_0 = 200$ comoving Mpc. (This parameter does not affect the results with beaming.) In (b), the thin curves show the absolute fractions of all quasars that are visible to the observer (short dashed) and that are not visible but produce measurable peaks in the forest (dotted).

For the purposes of this paper, we take a very simple toy model in which only a single (nearby) quasar induces fluctuations in the He\textsc{ii}-ionizing background; we assume that the cumulative background from other sources is uniform. This is certainly a simplification (Furlanetto 2009a), but we will defer a more comprehensive model to future, more detailed work. Figure 1 of Furlanetto & Dixon (2010) shows that this is a reasonable approximation in most cases of interest (i.e., near strong peaks in the radiation field).

We define a “peak” in the radiation field as any maximum in the He\textsc{ii}-ionizing background intensity for which $J > \sigma \langle J \rangle$, where $\sigma$ is a constant; for our simple model with only one foreground quasar, each such source can produce at most one peak, though more complex models with additional quasars and radiative transfer effects could in principle complicate the association. In particular, radiative transfer effects will likely increase the number of maxima, because shadowing by dense clumps can introduce additional features into the radiation field. However, we do expect such additional features to be confined to small scales, since such clumps typically have small cross sections. We might therefore hope to be able to identify the large-scale peaks due to individual quasars in any case—that is the approach we will take here, but see Section 5 for a more detailed discussion of this point in light of recent data. We will usually choose $\sigma = 1$, because the median ionizing background is a factor $\sim 3$ less than the mean (Furlanetto 2009a).

In practice, such peaks will be identified as minima in the “hardness ratio” $\eta = N_{\text{He}\text{ii}}/N_{\text{H}\text{i}} \propto \Gamma_{\text{H}\text{i}}/\Gamma$, the ratios of column densities in singly ionized helium and neutral hydrogen within a given absorber (Miralda-Escude 1993). We implicitly assume that $\Gamma_{\text{H}\text{i}}$ is uniform, so $\eta \propto 1/\Gamma \propto 1/J$. This appears to be an excellent approximation at $z \lesssim 4$ (Meiksin & White 2003; Croft 2004). This approach has the added benefit of eliminating any uncertainty in the density or temperature structure of the forest.

Note, however, that regions so close to their sources so as to be within both the proximity zones of He\textsc{ii} and H\textsc{i} may be missed by this technique. To estimate the importance of this
effect, let us compute the relative sizes of the He\textsc{ii} and H\textsc{i} proximity zones, $r_{\text{He}\textsc{ii}}$ and $r_{\text{H}\textsc{i}}$, which we define to be the points at which the ionization rate due to a quasar equals the rate due to the relevant ionizing background. (In fact some peaks will be detectable even within the proximity zone, so this is a conservative estimate.) We define the softness parameter $S$ as the ratio of the background ionization rates for the two species and assume that the quasar of interest has a spectral index $\alpha$, so that $L_\nu \propto \nu^{-\alpha}$. Then

$$\frac{r_{\text{He}\textsc{ii}}}{r_{\text{H}\textsc{i}}} \approx 2^\alpha S^{-1/2} \sim 0.3, \quad (1)$$

where for the last part we have taken $\alpha \sim 1.5$ (Telfer et al. 2002) and $S \sim 100$ (Bolton et al. 2006). The cross section of the H\textsc{i} zone is therefore only $\sim 0.1$ that of the He\textsc{ii} zones, so variations in the H\textsc{i} background should indeed have only a small effect on peaks in the hardness ratio.\textsuperscript{4}

We then define $r_p$ as the maximum transverse distance within which a quasar can sit and still produce a radiation peak. If the quasars are Poisson-distributed and the mean free path of an ionizing photon is $r_0$, the average radiation field is $\langle J \rangle = 3 N_0 J_0$ (Meiksin & White 2004), where $N_0$ is the average number of quasars inside one attenuation zone (with radius $r_0$), $J_0 = \langle L \rangle / (4\pi r_0)^2$, and $\langle L \rangle$ is the mean quasar luminosity (averaged over the luminosity function, which we take from Hopkins et al. 2007).

There is unfortunately considerable disagreement on the mean free path of these photons. At $z \sim 2.5$, models predict that $r_0 \sim 45 – 200$ comoving Mpc (e.g., Bolton et al. 2006; Faucher-Giguère et al. 2009). One method uses the IGM density distribution in simulations and calibrates to the observed average optical depth (Bolton et al. 2006), and it reproduces the abundance of H\textsc{i} Lyman-limit systems from Starrie-Lombrardi et al. (1994). However, it relies on ad hoc geometric assumptions about the absorbers. Fardal et al. (1998) and Faucher-Giguère et al. (2009) use photoionization modeling of absorbers in the H\textsc{i} forest; the latter reproduces the more recent mean free path measurements (for photons that ionize H\textsc{i}) of Prochaska et al. (2009) and Songaila & Cowie (2010). However, this method relies sensitively on the H\textsc{i} forest absorbers with $N_{\text{H}\text{i}} \sim 10^{15} – 10^{17}$ cm$^{-2}$, which are very difficult to measure, and other estimates give much smaller values (Fardal et al. 1998). The more recent data are calibrated to $z \sim 3.7$, so it also cannot account for possible evolution to the redshifts of interest, $z \sim 2.5$. Neither method takes into account the substantial fluctuations of the H\textsc{ii} ionizing background (Furlanetto 2009a).

Other arguments suggest that $r_0$ lies in the middle of this range. First, let us assume that the abundance of Ly$\alpha$ forest absorbers follows a power law $N_{\text{H}\text{i}} \sim 3^{-2/3}$, close to observational limits (e.g., Fardal et al. 1998). In the optically thin limit with uniform radiation backgrounds, the hardness ratio $\eta$ is spatially constant. We can therefore use the distribution of H\textsc{i} absorbers to relate the mean free paths of H\textsc{i} and He\textsc{ii} ionizing photons ($r_{\text{H}\text{i}}$ and $r_0$, respectively):

$$r_{\text{H}\text{i}} = r_0 \sqrt{\eta / 4}. \quad (2)$$

Faucher-Giguère et al. (2009) estimate that $r_{\text{H}\text{i}} = 85 (1 + z)^{-1/4} \text{Mpc}$, which matches the Prochaska et al. (2009) measurement at $z = 3.6$ very well, although the redshift evolution is uncertain. In that case, $\eta \sim 40 – 80$ (Shull et al. 2004; Zheng et al. 2004; Fechner et al. 2006; Fechner & Reimers 2007) implies $r_0 \sim 110 – 160 \text{Mpc}$ at $z \sim 2.5$.

A separate argument comes from matching the (measured) emissivity of the quasar population with the observed optical depth of the He\textsc{ii} forest. In the fluctuating Gunn–Peterson approximation, $r_0 \gtrsim 100 \text{Mpc}$ overproduces the ionization rate compared to observations (Dixon & Furlanetto 2009), although there is an uncertain correction factor in this model.

We therefore take $r_0 = 45$ comoving Mpc as a fiducial model but show results for larger values as well.\textsuperscript{5} Then we find $r_p \approx r_0 \sqrt{L/L_\odot}$, where

$$\bar{L} = 3N_0 \sigma \langle L \rangle \approx 5 \times 10^{12} \text{ergs s}^{-1} \left[ \frac{r_p (1 + z)^3}{45 \text{Mpc}} \right] L_\odot \quad (3)$$

is a characteristic luminosity. (Here the factor $1 + z$ converts our physical coordinates into comoving units.) Quasars must sit inside this region and intersect the Ly$\alpha$ forest skewer in order to produce an observable peak. For reference, a bright quasar ($\sim 10^{12} L_\odot$) has $r_p \sim r_0 / \sqrt{5} \sim 20$ comoving Mpc with our fiducial value for $r_0$; $r_p \sim 12$ comoving Mpc for $r_0 = 150$ comoving Mpc.\textsuperscript{6}

We now suppose for simplicity that each quasar has a constant luminosity over a lifetime $t_Q$. Of course, real sources are likely to have much more complex light curves—for example, the Hopkins et al. (2005a) model assumes that quasars are very long-lived, with strongly variable luminosities over their total lifetimes. In this context, our parameter $t_Q$ would roughly describe the period over which the luminosity remains near its maximum value. The above estimate shows that the cross section for a quasar to create a peak is $r_p^2 \propto L$, so a decrease in luminosity by a factor of 10 strongly decreases the available space for quasar–peak pairs and so change their abundance dramatically. (We comment on some of the other implications of this model in Section 6.)

If quasars have a finite lifetime $t_Q$, the induced radiation peak along a nearby line of sight can be displaced radially from the quasar location, and—because of light travel time delay—the quasar also may not be visible when the peak is observed. To compute the probability to have a “bare” peak (i.e., without an associated quasar), we note that the quasar and peak are both visible (1) once the peak has moved within a distance $r < r_p$ of the source and (2) before $t_Q$ has elapsed. The first corresponds to a minimum time after the quasar appears of

$$t_{\text{min}} = \frac{r_p - \sqrt{r_p^2 - r_\perp^2}}{c}, \quad (4)$$

where $r_\perp$ is the quasar’s impact parameter from the Ly$\alpha$ forest skewer. Before $t_{\text{min}}$, the peak along the Ly$\alpha$ forest skewer is at least $r_p$ in front of the quasar and is invisible. Of course, if

\textsuperscript{5} An alternative approach is to scale the proximity zone to the He\textsc{ii} ionization rate, $\Gamma$. In that case, we remove the uncertainty in $r_0$ but replace it with equivalent uncertainty in $\Gamma$.

\textsuperscript{6} Here we provide $B$-band luminosities, although of course the relevant quantities for the He\textsc{ii} ionizing background trace much higher energy photons. We thus implicitly assume in our calculations that all quasars have the same spectral shape. In fact, there appears to be a fair amount of variation between sources (Telfer et al. 2002) which should be included in a more sophisticated model. This could cause some faint optical quasars to nevertheless induce strong peaks, and some bright quasars to produce weaker peaks than expected.

\textsuperscript{4} We will also see below that these very nearby peaks are relatively uninteresting for constraints on quasar lifetimes.
If all quasars have a fixed luminosity, so that \( r_p \) is constant across the population, then the fraction of peaks with quasar associations is \( F_p = N_{pq}/(N_{ph} + N_{pq}) \), where

\[
N_{pq} = \pi \int_0^{r_{max}} dr_\perp r_\perp c[t_Q - t_{min}(r_\perp)] \quad \text{and} \quad (6)
\]

\[
N_{ph} = \pi \int_0^{r_{max}} dr_\perp r_\perp c[\Delta t_{max}(r_\perp) - \max(t_{min} - t_Q, 0)] \quad (7)
\]

are, respectively, the volumes within which quasars can sit and have a visible peak (or not). Here, \( r_{max} \) enforces the requirement that \( t_{min} \leq t_Q \); it is

\[
\frac{r_{max}}{r_p} = \sqrt{1 - (1 - \tilde{r}_Q)^2} \quad (8)
\]

if \( \tilde{r}_Q \equiv c t_Q / r_p < 1 \) and unity otherwise. The final factor in \( N_{ph} \) accounts for the time lag between the quasar shutting off and the peak reaching the proximity zone, in cases where \( t_Q < t_{min} \).

The integrals in Equations (6) and (7) can be performed analytically; the results scale roughly as \( \propto L_\perp \), with a suppression at large luminosity because of the finite lifetime limits (even though bright quasars have large proximity zones, they can still shut off before the peak becomes visible). Of course, we must actually integrate \( N_{pq} \) and \( N_{ph} \) over the quasar luminosity function. Because these factors scale like \( r_\perp^2 \propto L \), the most luminous quasars are by far the most important for generating peaks in the radiation field.

Figure 1(a) shows the resulting fractions for several different mock surveys. In order to better mimic real surveys, we take a minimum luminosity threshold when calculating the fraction of observed associations, though not when calculating the total number of peaks (i.e., we limit \( L \) in the numerator of \( F_p \) but not in the denominator). We do not (yet) limit the spatial extent of the survey, instead assuming that all quasars can be identified out to the appropriate \( r_p(L) \), which is in principle measurable from each quasar’s luminosity. In practice, this would require a survey that is deepest near the Lyα forest line of sight.

The thick solid curve takes \( L > 10^{11} L_\odot \) and \( r_0 = 45 \) comoving Mpc at \( z = 2.5 \). The fraction of associations increases rapidly at \( t_Q \lesssim 3 \times 10^7 \) yr and then flattens out at larger lifetimes. For small lifetimes, we expect the result to be \( \sim \tilde{r}_Q^2 \), which is the fraction of the proximity zone for which the light travel time is less than \( t_Q \). This is indeed roughly correct; once \( \tilde{r}_Q \gtrsim 1 \), the curves flatten significantly because the more distant quasars only provide observable peaks for brief windows of time in any case.

The dotted curve shows how the fraction varies with the survey depth, taking \( L > 10^{12} L_\odot \). Clearly a shallower survey strongly reduces the number of observed associations. However, note that decreasing the limit below \( 10^{11} L_\odot \) has very little effect. One need only identify those quasars responsible for strong peaks, which are primarily bright and moderate luminosity sources. To produce a peak, faint sources must already be so close to the line of sight that their available volume is small. However, although fewer peaks have associations, the variation of the curves with \( t_Q \) is relatively constant with \( L \), so a wide, shallow survey may be just as effective as a deeper one, if one is confident enough about modeling the fainter quasar population.

The thin solid curve takes \( r_0 = 200 \) comoving Mpc; we find that the fraction of associations is roughly proportional to \( r_p^2 \propto r_0^{-1} \) at short lifetimes. A larger attenuation length increases the fraction of peaks with quasars, because the additional sources illuminating each point effectively decrease \( r_p \) (and hence time delay effects) in order to overcome the background from the other sources. The dependence is substantial, so a more accurate estimate of the mean free path will be essential for detailed constraints.

Finally, the long-dashed curves assume a survey comparable to Worseck et al. (2007); again the thick and thin curves take \( r_0 = 45 \) and 200 comoving Mpc, respectively. We take \( L > 10^{11} L_\odot \), only include peaks with \( \sigma > 8 \), and only identify quasars within 12 comoving Mpc of the Lyα forest skewer. These factors decrease the dependence on \( t_Q \) (and hence make the survey less sensitive), largely because of the high peak threshold: quasars must be very close to the line of sight in order to produce such strong peaks. These nearby sources do not provide much constraining power, because the light travel time is then small compared to \( t_Q \); surveys for bright quasars at distances near \( r_p \) are most efficient. Nevertheless, short lifetimes \( (t_Q \sim 10^6 \text{ yr}) \) would imply very few observable associations with this kind of survey (see Section 5), and very long lifetimes \( (t_Q \gtrsim 10^8 \text{ yr}) \) would imply almost perfect association.

### 3. QUASARS AND RADIATION PEAKS: BEAMING

We now switch focus to models with infinite lifetime but anisotropic quasar emission (or “beaming”). For concreteness, we will use a simple biconical emission model, in which two oppositely directed beams each have opening angle \( \Omega \).

In this case the calculation is conceptually simple: how often does a beam that remains invisible to the observer intersect the Lyα forest line of sight between the front and back edges of the proximity zone? Some visible quasars will have such intersections, some will have none, and some invisible quasars will still cause peaks; our accounting must include all these possibilities. (Note that quasars whose beams do not intersect either the observer’s line of sight or the Lyα forest skewer remain entirely invisible and can be ignored.)

We use a Monte Carlo model to compute these probabilities.\(^7\)

The thin curves in Figure 1(b) show (1) the fraction of quasars that are visible to the observer and produce visible peaks (short-dashed curve) and (2) the fraction that are invisible to the observer but still produce a peak (dotted curve). The former simply increases with \( \Omega \), of course.\(^8\) The latter initially increases (as quasars become more likely to intersect the skewer) and then decreases (as quasars become more likely to be seen by the observer).

To generate predictions relevant to observations, we must include quasars of all luminosities, as before. However, if we

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\(^7\) Without the limits imposed by the proximity zone, an analytic calculation is straightforward—in fact every visible quasar produces a peak somewhere—but requiring some part of the beam to strike the skewer within \( r_p \) of the quasar’s location makes such a model unwieldy.

\(^8\) Note again that all quasars produce “peaks” somewhere along the line of sight, but we do not count them unless they are within the proximity zone.
assume (as in our fiducial model) that we detect all quasars within their respective $r_p(L)$, then the results become independent of luminosity because each quasar is treated identically (this differs from the finite lifetime case, where $r_p$ introduces a second physical scale). If, however, $r_{\text{max}}$ is fixed (as in a real survey), then the integration over the luminosity function becomes necessary. Similarly, if the survey is not infinitely deep, the minimum luminosity threshold introduces luminosity dependence because some associations with faint quasars will be missed.

The thick solid curve in Figure 1(b) shows results for a survey with $r_{\text{max}} = r_p(L)$ and $L > 10^{11} L_\odot$. The number of bare peaks can be substantial; roughly two out of three peaks will have no visible association if $\Omega \sim \pi/2$, with the ratio declining very rapidly at smaller opening angles. As in the finite lifetime case, a shallower survey misses associations. However, in this case the shape of the curve as a function of $\Omega$ does change with the luminosity threshold, becoming slightly more sensitive to variations in $\Omega$ as the survey deepens.

The long-dashed curve again shows a survey similar to Worseck et al. (2007), which only includes strong peaks and nearby quasars. Because there is no physical scale other than $r_p$ in the problem, simply increasing $\sigma$—which affects all quasars equally—does not affect the fraction of bare peaks. On the other hand, limiting $r_{\text{max}}$ does, because it eliminates the possibility of finding more distant luminous counterparts. However, with the large $\sigma$ imposed here nearly all peaks are sourced by quasars within the surveyed region, so the finite area makes only a small difference to the final curve, which is mostly determined by the depth of the survey.

It is worth emphasizing that the beaming case is somewhat more robust to observational uncertainties, because it does not depend on $r_0$ (at least in our simplified model).

To this point, we have considered finite lifetimes and beaming as separate, isolated phenomena. But of course even beamed quasars must have finite lifetimes, even if relatively long. To keep our models simple, we have separated these two phenomena, though of course in reality one must jointly constrain the two parameters. In general, both short lifetimes and beaming decrease the number of associations, so observations of a given fraction of bare peaks will suggest a mixture of short lifetimes and near isotropic emission or long lifetimes and strong beaming.

However, even considered in isolation, we will see in Section 5 that data can put interesting constraints on these parameters, because combining finite lifetimes and beaming cannot increase the fraction of associations over and above our models that consider each in isolation. In order to keep the results as easy to interpret as possible, we will therefore consider them as separate effects, deferring a combined model to more detailed work in the future.

4. PEAK–QUASAR ASSOCIATIONS

Although the lifetime and beaming angle are degenerate so far as the fraction of “bare” peaks are concerned, more detailed information can distinguish these two scenarios. Here we briefly show that the relative radial locations of the peaks and their associated quasars is one way to achieve this.

Clearly, if each quasar emits isotropically over an infinite lifetime, it illuminates every point in the universe, so the brightest point along a nearby Ly$\alpha$ forest skewer (at a radial distance from the observer $r_{\text{peak}}$) will lie at the same radial distance as the quasar: i.e., if $\theta$ is the angle between the Ly$\alpha$ forest skewer and the ray joining $r_{\text{peak}}$ and the quasar, then $\theta = \pi/2$ for every source, barring complex radiative transfer effects and errors in localizing the quasar and peak. Deviations from this simple expectation therefore indicate more complex quasar properties, such as finite lifetimes or beaming.

4.1. A Finite Lifetime

With a finite lifetime, a quasar visible through both its direct emission and through its influence on a point in the IGM must satisfy a time delay criterion: the difference in light travel time along these two paths $\Delta t$ must be no greater than $t_Q$. In terms of the angle $\theta$, this time delay is

$$\Delta t = (r - d_{\text{LOS}})/c = (1 - \cos \theta) r / c = \left( \frac{1 - \cos \theta}{\sin \theta} \right) r_{\perp} / c,$$

where $r$ is the total distance from the quasar to the nearest point that it illuminates and $d_{\text{LOS}}$ is the radial distance between that same point and the quasar. This is an increasing function of $\theta$, so points closest to the observer have the least delay, and it increases monotonically as $\theta$ approaches $\pi/2$.

We will construct the probability distribution of the angle $\theta$ in a finite lifetime model (recall that it is a delta function at $\theta = \pi/2$ for the fiducial infinite lifetime model). If the quasar turned on a time $t$ in the past, only points with $\Delta t < t$ are illuminated, and the peak is at the point with the largest $\theta$. Assuming a uniform distribution of quasar ages, the cumulative distribution of peak locations is therefore

$$P(<\theta) = \frac{\Delta t}{t_Q} = \left( \frac{1 - \cos \theta}{\sin \theta} \right) \frac{r_{\perp}}{c t_Q}.$$  

The left panel of Figure 2 shows this distribution for several impact parameters $r_{\perp}$, scaled to $c t_Q \approx 30(t_Q/10^8 \text{ yr})$ Mpc. Two points are immediately obvious. First, $\theta < \pi/2$ always; once the quasar illuminates this point of absolute closest approach, the peak must remain there until the quasar shuts off. Thus, we expect a clear asymmetry between the forward and backward directions. Second, the distribution depends strongly on the impact parameter from the skewer. Nearby quasars have short delays, so $\theta = \pi/2$ is most common. But those at relatively large impact parameters only rarely have the timing just right to attain $\theta = \pi/2$. Thus, faint quasars—which must be nearby to influence the radiation field—provide little additional information on finite lifetimes, and surveys for bright quasars over wide areas are most productive.

Note that here we have not restricted ourselves to quasars with visible peaks within a distance $r_p$ from the source. The importance of this restriction depends on the impact parameter $r_{\perp}$; those peaks with $\cos \theta \sim 1$ will be difficult to identify in practice.

4.2. Quasar Beaming

Now we consider the distribution of $\theta$ in a beaming model with infinite lifetime; specifically, biconical emission. More complicated emission geometries are of course possible and can dramatically change the estimates in this section. For a quantitative picture, we again turn to the distribution of $\theta$. In the beamed case, quasar–peak pairs visible to the observer will typically not have $\theta = \pi/2$, because the beams can only subtend (at most) an angle $\Omega$ from $\theta = 0$ or $\pi$ (along the

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9 We assume here that the quasar is effectively at an infinite distance from the observer.
radial direction). The right panel of Figure 2 shows the resulting cumulative probability distributions of \( \theta \) for a range of opening angles (generated with a Monte Carlo model).\(^{10}\)

As expected, when each beam has \( \Omega = \pi \) (i.e., isotropic emission), the peak is always located perpendicular to the line of sight. As \( \Omega \) decreases, the probability of this configuration decreases rapidly, and by \( \Omega = \pi/2 \), it is vanishingly rare. Instead, the peak drifts farther and farther from the perpendicular, because the illuminated region is oriented more and more directly toward (or away from) the observer.

There are two clear differences from the finite lifetime case. First, the beaming results are distance-independent, because there is no physical scale in the problem (although “peaks” beyond \( r_p \) will no longer be visible in practice). Second, the distributions are symmetric about \( \theta = \pi/2 \), because we assume two beams directed in opposite directions; \( \theta > \pi/2 \) indicates that different beams illuminate the skewer and observer. The second difference therefore depends on the particular model of quasars, but the first will unambiguously distinguish finite lifetimes from geometric effects.

5. COMPARISON TO EXISTING OBSERVATIONS

So far, searches for neighboring quasars have been conducted along two of the five lines of sight with He II Ly\( \alpha \) forest data. The best sample so far surrounds the line of sight to HE 2347–4342, whose He II forest has been extensively studied (Zheng et al. 2004; Shull et al. 2004; Fechner & Reimers 2007; Shull et al. 2010). Worseck et al. (2007) searched for nearby quasars with \( L_{\text{min}} \gtrsim 1-2 \times 10^{11} L_\odot \) and a maximum impact parameter \( \sim 12 \) comoving Mpc. They discovered two nearby quasars, both with associated peaks in the high-energy radiation background (actually identified as troughs in the hardness ratio \( \eta \)).\(^{11}\) Three other regions of the spectrum have a radiation field at least as hard as these (with \( \sigma = 8 \)), so the fraction of associations is 2/5.

The second skewer is toward Q0302–003. Heap et al. (2000) identified a strong transmission feature near \( z = 3.05 \). Jakobsen et al. (2003) subsequently identified a quasar at a projected distance of just 1.77 comoving Mpc from this feature. Worseck & Wisotzki (2006) later performed a deeper search (to comparable magnitude and volume limits as above) and identified one more quasar within \( \sim 5 \) Mpc (projected) of the He II Ly\( \alpha \) forest line of sight and a third inside the classical proximity zone of Q0302–003 (we ignore the last, since its effects are difficult to disentangle).

Worseck & Wisotzki (2006) find peaks in the hardness of the radiation background near the locations of all of these quasars. They do not quantify the number of peaks without quasars, but visual inspection of their Figure 7 show that the sample also contains two other hardness peaks of comparable amplitude to those with known quasars. If these are included (so that the fraction of associations is 4/9 across both lines of sight), we can estimate the likelihood of this result given the various parameter sets. Assuming that each peak provides an independent test, and taking the probability of successfully finding a nearby quasar from Figure 1 (the long-dashed curves match the survey parameters reasonably well), then the probabilities to find exactly four associations in the sample are (0.17%, 2.0%, 14%, 23%, 51%) for \( t_Q = (0.3, 0.5, 1, 3, 10) \times 10^7 \) yr, respectively, if we take \( r_0 = 45 \) comoving Mpc. Thus, with this single line of sight we can rule out at high confidence lifetimes of \( t_Q \gtrsim 5 \times 10^8 \) yr (or even significant variability on those timescales) or \( t_Q \gtrsim 10^9 \) yr.

However, taking a larger mean free path (\( r_0 = 200 \) comoving Mpc) changes the constraints. In that case, the probabilities to find exactly four associations in the sample are (0.02%, 4.9%, 26%, 8.2%, 1.2%) for \( t_Q = (0.1, 0.3, 1, 3, 10) \times 10^7 \) yr, respectively. We can still therefore rule out long lifetimes \( t_Q \gtrsim 10^8 \) yr by the lack of perfect associations, but we cannot place as strong constraints at the short end. Note that the constraints do not improve much more at large \( t_Q \), because the distribution flattens out when \( r_Q \) exceeds unity for bright quasars.

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\(^{10}\) Note that we normalize these distributions to unity, so we include only those sources that are both visible and create peaks along the line of sight; the other configurations discussed in Section 3 are not relevant for this test.

\(^{11}\) They also report a third quasar just below their survey limit, which we do not include to ensure completeness. However, because it lies very close to one of the other two quasars, it actually adds no additional information.
We also find probabilities of (0.11%, 8.5%, 9.5%, 0.5%) to find exactly four associations if $\Omega = (60^\circ, 90^\circ, 135^\circ, 180^\circ)$, respectively.\footnote{The small chance for isotropic emission ($\Omega = 180^\circ$) accounts for quasars below the minimum luminosity limit.} Thus, here we can place strong constraints, ruling out any beaming scenarios with $\Omega \lesssim 90^\circ$ as well as isotropic emission (at least with the infinite lifetime approximation); these are independent of the uncertainty in $r_0$ in our simple model where the nearest source provides a clear peak. Note that finite lifetimes and beaming both decrease the observed ratios, so combined models constrain small $\Omega$ even more tightly (although isotropic emission with finite lifetimes is permitted).

In this analysis, we have used the low signal-to-noise Far-Ultraviolet Spectroscopic Explorer (FUSE) He ii spectra available at the time of the quasar searches (Worseck \& Wisotzki 2006; Worseck et al. 2007) in order to allow a reasonably uniform sample across both spectra. Very recently, Shull et al. (2010) observed HE2347–4342 with the newly installed Cosmic Origins Spectrograph (COS) on the Hubble Space Telescope. The remarkable improvement in the He ii Lyα forest spectrum clearly shows the peaks and troughs in the hardness ratio (their Figure 7), and in principle this makes our test much easier. In this case it is very easy to identify peaks with $\sigma \gtrsim 5$; in fact the spectrum is so clean that small-scale radiative transfer effects are most likely visible, because multiple peaks often appear very close together.

In our simple model, we would attribute every such peak to an independent quasar—but more likely, the density structure of the IGM modulates the small-scale radiation field, creating additional features. Because dense clumps that can shadow quasar radiation are small, we only expect such features to affect the small-scale structure of the hardness ratio, but the actual scales that are relevant are hard to predict without detailed radiative transfer calculations.

It is therefore somewhat difficult to identify rigorously the independent peaks in the spectrum (i.e., those genuinely due to different quasars), so a more detailed simulation is likely necessary in order to utilize these data fully. For a simple estimate, we count the number of regions of extent $r_n \sim 20$ comoving Mpc with peaks inside them and use that as a proxy for the true number of independent peaks. We count seven such regions in the range $z = 2.4$–2.72 (although several are very near our threshold); the spectrum cuts off below this redshift, and at higher values He ii reionization may interfere with our simple model (Dixon \& Furlanetto 2009; Furlanetto \& Dixon 2010; Shull et al. 2010). Only one of the Worseck et al. (2007) associations sits in this range, so along this segment we have 1/7 peak-quasar associations. Using $\sigma = 5$, we find the probability of this result to be (4.4%, 24%, 35%, 8.0%, 0.43%) for $t_{Q} = (0.1, 0.3, 1, 3, 10) \times 10^7$ yr, respectively, and (39%, 27%, 3.2%, $\approx 0$) if $\Omega = (60^\circ, 90^\circ, 135^\circ, 180^\circ)$, respectively.

Because of the additional peaks visible in this cleaner spectrum, these data are more tolerant of short lifetimes and tight beaming but less tolerant of long lifetimes and isotropic emission compared to the FUSE spectra. This is because the additional peaks decrease the apparent fraction of associations from 2/5 to 1/7 along this line of sight. As emphasized above, however, the data here are sufficiently precise that simulations are clearly necessary to exploit it fully. The difficulty of rigorously associating peaks and sources in these new data may indicate that a statistical approach, rather than one-to-one peak-quasar associations, will be more robust.

For most of these quasars, the local minima in $\eta$ coincide in redshift with the quasars themselves, which implies that isotropic emission and relatively long lifetimes are good approximations. However, one source (at $z = 2.69$ toward HE 2347–4342) has a peak somewhat in front of it according to the FUSE spectrum. Worseck et al. (2007) estimate that $t_{Q} \gtrsim 25$ Myr from this coincidence. According to our models, the position in front of the quasar is suggestive of a finite lifetime as an explanation, but it could be explained equally well by a beaming model. On the other hand, the COS spectrum shows a peak at $z = 2.69$ as well as the one at lower redshifts, which would easily be consistent with longer lifetimes or isotropic emission.

In any case, confusion from more distant sources as well as redshift errors can easily mimic this level of displacement in individual sources, so statistical samples are necessary for strong constraints based on the relative positioning of peaks and quasars.

6. DISCUSSION

We have examined how the transverse proximity effect, observed through a combination of the He ii and H i Lyα forests, can help to constrain quasar properties. Using simple toy models, we showed how finite source lifetimes and beamed emission affect the statistical association between peaks in the He ii ionizing background and quasars. Both scenarios can substantially decrease the probability that the source causing a given peak is visible to a distant observer. Finite lifetimes break such associations when $c t_Q$ is less than the “proximity radius” within which a quasar’s radiation is more important than the accumulated background. Quasars with beamed emission may or may not be visible to both the Lyα forest skewer and the observer for purely geometric reasons. As such, these models are less sensitive to the impact parameter of the quasar.

We have compared briefly with the existing data, which include relatively small surveys for quasars around two lines of sight. Applied to these data, which show only a few associations, this technique suggests that $t_{Q} \lesssim 10^8$ yr (with some weaker indications that $t_{Q} \gtrsim 3 \times 10^6$ yr as well). Similarly, it appears to rule out even very small ($\lesssim 60^\circ$) opening angles or isotropic emission (unless a finite lifetime is assumed). Nevertheless, even with such sparse data and a simple model, these constraints are already competitive with existing ones on quasar lifetimes and beaming, both from the H i forest (Gonçalves et al. 2008; Kirkman \& Tytler 2008) and from other techniques (e.g., Soltan 1982; Yu \& Tremaine 2002).

Of course, our simple toy models, which focus only on the single nearest source and ignore radiative transfer, are not sufficient to claim rigorous constraints. Improved numerical or Monte Carlo models can better test the importance of the accumulated background of distant quasars, errors in quasar locations, and errors in peak detection in the He ii forest. The impressive COS He ii spectrum from Shull et al. (2010) illustrates some of these difficulties, as one can clearly trace the peaks and troughs of the ionizing background. This background shows a great deal of structure, some likely due to radiative transfer effects, and it is difficult to determine by eye which peaks to associate with an individual source. Nevertheless, the constraints suggested by our toy model show that this is a very promising technique for the future, once more sophisticated modeling is included.
The mere presence or absence of a nearby quasar is also only the first bit of information from such surveys; the distribution of peak locations around quasars contains much more. Causality dictates that sources with finite lifetimes create peaks in front of (or at worst coincident with) the source, while beamed quasars can have their peaks behind the sources. The existing surveys have three peaks nearly coincident with their sources and one (possibly leading); this provides weak evidence for finite lifetimes and/or anisotropy, but much better modeling is needed to interpret the data fully.

In designing a survey, we have found that the brightest neighbors are the most useful, because they have the largest proximity zones and produce the most obvious peaks. Faint quasars must be extremely close to the line of sight in order to create a peak; if they are so close, then the light travel time is small so they do not efficiently constrain finite lifetimes. (The same is true of bright quasars very near to the line of sight; the strongest constraints on lifetimes will be provided by quasars at moderate distances from the Lyα forest skewers.)

We have argued that this method has two advantages over more traditional searches involving just the Hα forest (Worseck & Wisotzki 2006). First, the transverse proximity zone is much larger in He II, because only (rare) quasars contribute to the high-energy ionizing background and because the IGM attenuation length is several times smaller. Second, and more important, comparing the He II and H I Lyα forests provides a direct measurement of the hardness of the radiation field, robust to variations in the underlying IGM density and temperature. This avoids a substantial bias in the H I proximity effect (Faucher-Giguère et al. 2008).

Our tentative results from these toy models are consistent with the detection of the transverse proximity effect through metal lines by Gonçalves et al. (2008), who estimated $t_\alpha \sim 3 \times 10^7$ yr for two quasars. However, they may be inconsistent with Kirkman & Tytler (2008), who used a large sample of quasars with $\sim$Mpc separations to search the H I forest for the transverse proximity effect. They found no evidence for enhanced transmission in front of the quasars but decreased transmission behind them. They hypothesize that the increased gas density around the quasar hosts may cancel the expected increase in transmission in front of the quasars; in that case, the decreased transmission behind the foreground objects implies that the quasar light has not yet reached these regions, which in turn implies a short lifetime (or at least variability timescale) $\sim 10^8$ yr. Our constraints on variability on these very short timescales depend on the treatment of the data and so require more careful investigation.

There are, in addition, many simplifications in our model. In addition to the inevitable measurement uncertainties in real experiments, we neglect the detailed structure of the forest and radiative transfer, which can induce small-scale features in the background. In the finite lifetime case, the attenuation length of He ii-ionizing photons is an important parameter, but one that is very difficult to measure directly. We have also assumed that optical surveys suffice to identify UV-bright quasars, but in reality there is substantial scatter in their far-UV properties (Telfer et al. 2002; Scott et al. 2004), which will degrade the correlation.

Although we have focused on what the proximity effect can reveal about quasar lifetimes and beaming, there is more interesting physics to be gleaned. For example, seeing any proximity effect at all implies that a quasar cannot be “flickering” more rapidly than the equilibrium time of the gas ($\sim 3 \times 10^6$ yr at $\Gamma \sim 10^{-14}$ s$^{-1}$, near the expected cosmic mean), or the mismatch from time delays wipes out the proximity effect. Because this timescale is much longer than that for H I, the resulting “flickering” timescale is actually significant compared to our expectations for quasar lifetimes. Thus, the H II forest can be used to measure long-term variability and perhaps even to constrain popular models like an exponentially decreasing quasar luminosity or the more complex light curves of Hopkins et al. (2005b). In either case, we might expect to find low-luminosity quasars (in their late stages of existence) correlated with surprisingly strong peaks in the hard ionizing background. This may be very interesting in light of the rapid variability timescales suggested by Kirkman & Tytler (2008).

Another possibility, in the context of finite quasar lifetimes, is to exploit the bare peaks by looking for a correlation between these and “post-quasar” galaxies, perhaps with a recently concluded burst of star formation or evidence for recent strong mechanical feedback from the quasar. Alternatively, in a beaming model, one would instead search for correlations with galaxies showing signatures of obscured quasars, such as rapid ongoing star formation.

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