Chapter 9

Investigation of a Possible Void

After proposing the ionization model for the proximity effect, Bajtlik, Duncan and Ostriker (1988) examine the suggestion by B. Paczyński that an isotropically emitting foreground quasar could also deplete the Ly α clouds in the nearby lines of sight to other quasars. The possibility of such a two-quasar proximity effect has led to some searches for voids in the Ly α forest (e.g., Fernández-Soto et al. 1995), but until now only two Mpc-sized voids have been found in the literature (see section 9.1).

With two quasars, additional factors come into play. For example, if the foreground quasar radiates anisotropically, a void might still be observed in the other spectrum, although generally not at the same redshift as that of the foreground quasar. But the anisotropy would also mean that we might fail to see a void even if a sufficiently bright quasar is seen close enough to the line of sight. Alternatively, we might see a void in the vicinity of a quasar that appears too faint to have caused the void; or in the most extreme situation, we may observe no quasar at all. The same effects could also appear if the foreground quasar varies on time scales shorter than the light-travel time to the void or the equilibriation time scales for the Ly α clouds. This could make it difficult to use the two-quasar proximity effect as an estimate of the ionizing UV background at a void.

On the other hand, these very difficulties would make interesting research topics in themselves. With large enough statistics it could be possible to determine precisely whether the quasar radiation is "beamed" or obscured in certain directions, as in some models of the active galactic nuclei—and, if so, what shape or opening angles the radiation should have.

9.1 Estimate of Void Size

Looking at the spectrum of HE 0940, there is a conspicuous region of approximately 30 Å that seems to be relatively free of lines. One possible cause is of couse that there is another quasar along the line of sight, causing the void by means of photoionization.

If we consider that the possible void could extend the entire distance between the line at 4336.4 Å and the line at 4367.4 Å, this corresponds to a redshift interval of

$$\Delta z = 2.592551 - 2.567062 = 0.025489 \tag{9.1}$$

Converting this to a luminosity distance using equation (8.7) and the parametrization for the Hubble parameter $H_o = 100h$ km s^{-1} Mpc^{-1} yields an estimated void size of $3.2h^{-1}$ Mpc for $\Omega_o = 1$, or a size of $4.9h^{-1}$ Mpc for $\Omega_o = 0.2$. Figure 9.1 illustrates better how the luminosity distance corresponding to this particular redshift interval depends on the density parameter.

The estimate above must be taken as an upper limit for the size of the possible void, because there is at least one small line visible within this range. Further small lines were identified upon closer inspection (see section 9.2), so if the region does turn out to be statistically significant it would technically be what Kovner and Rees (1989) call a "clearing," to distinguish strongly underdense regions from those containing no lines at all. In the following, however, the term "void candidate" or "void" will continue to be used loosely to refer to the 30 Å region under consideration.

Even if any such lines were ignored completely, the resulting void would still be smaller than two others found in the literature. Dobrzycki and Bechtold (1991a,b) report a void in the spectrum of Q0302–003 between $\lambda \approx 5050$ Å and $\lambda \approx 5100$ Å, which is a redshift interval of $\Delta z \approx 0.04$ at $z \approx 3.17$. According to equation (8.7), this corresponds to a size of approximately $3.5h^{-1}$ Mpc and $5.6h^{-1}$ Mpc for $\Omega_o = 1$ and $\Omega_o = 0.2$, respectively.[1] Srianand (1997) also reports a void of about 50 Å in the spectrum of Tol 1038–2712, with $\Delta z = 0.0423$ centered at $z = 2.18635$. But since it is at a lower redshift, the estimated size is larger: $7.1h^{-1}$ Mpc and $10.6h^{-1}$ Mpc for $\Omega_o = 1$ and $\Omega_o = 0.2$, respectively.

9.2 Presence of Small Lines

Since there was the small but obvious absorption line at 4354 Å, the entire 30 Å region was studied more closely to determine the significance level of any other possible lines. Using the method described in section 6.3, the $5\,\sigma$ detection limit was determined to correspond to $\log N_{min} = 12.5$. The line at 4354 Å has a column density of $\log N_{\rm HI} = 13.0$ and—not surprisingly—was thus significant to the $15\,\sigma$ level. Two additional lines above this detection limit were also found at 4340 Å and 4358 Å. The errors in position and column density were twice that of the first line, and the errors in b were four and five times higher (see Table 9.1). However, the fitted column densities of $\log N_{\rm HI} = 12.9$ and $\log N_{\rm HI} = 12.7$, respectively, correspond to $12\,\sigma$ and $8\,\sigma$ features; so they were not dismissed.

[1] Dobrzycki and Bechtold quote proper sizes of $4.5h^{-1}$ and $11.25h^{-1}$ Mpc for the given values of Ω_o. However, in the text above the sizes were given in terms of luminosity distance rather than proper distance for convenience and for consistency, so that the three cases could be compared directly.

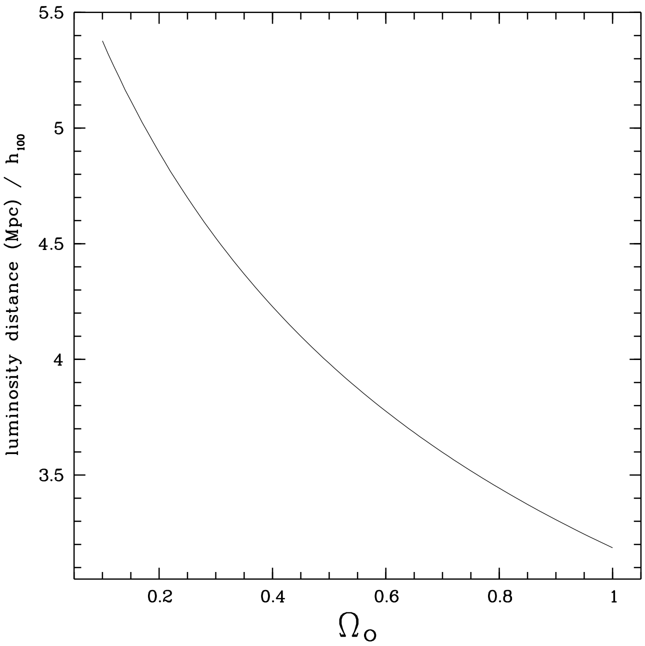

Figure 9.1: *Void size vs. density parameter Ω_o*

λ	σ_λ	z	$\log N_{\rm HI}$	$\sigma_{\log N}$	b	σ_b
4336.37	0.17	2.567062	13.41	0.15	34.9	11.4
4339.71	0.11	2.569806	12.87	0.20	27.7	27.9
4354.12	0.05	2.581664	12.99	0.08	20.2	5.0
4357.84	0.17	2.584723	12.69	0.19	25.2	19.4
4367.36	0.05	2.592551	13.21	0.07	27.6	4.7
4369.89	0.04	2.594638	16.97	0.70	31.1	3.6

Table 9.1: *Lines in and bounding the void candidate.*

Dobrzycki and Bechtold (1991b) also found lines in their simulations of quasar-induced voids in absorption spectra. They generated artificial spectra from the usual redshift and column-density distributions and a Gaussian Doppler-parameter distribution with $\langle b \rangle = 35$ km s^{-1} and $\sigma_b = 7$ km s^{-1}. The interesting result is that even when the foreground QSO was very strong, significant lines remained even in the part of the spectrum where the quasar's influence was greatest. The authors therefore concluded that the first signature of a two-quasar proximity effect is a lack of weak lines, rather than a lack of lines in general. This makes sense when one considers that lines on the linear curve of growth are already so close to the detection limit that they will quickly fall below it if their column densities decrease by a small amount; while strong lines will tend to remain saturated.

It is therefore interesting to note that in the present void candidate only relatively small ($N_{\rm HI} \leq 10^{13}$) lines are visible. One explanation could be that the region represents merely a region of low density in the large-scale distribution of matter (or at least of neutral hydrogen), rather than the sphere of influence of a foreground quasar.

9.3 Significance of the Void

Probably the best way to estimate the significance of a possible void in a spectrum is to create simulated spectra with the same resolution, signal-to-noise ratio, and sampling as their observed spectrum, and to analyze these spectra with the same automated routines used on the actual data. This is what done by Dobrzycki and Bechtold (1991b), who then adjusted the total number of lines and the power-law exponent γ in their simulated spectra until they obtained the same distribution of gaps as in the actual spectrum. The best-fit parameters were then used to generate 50,000 simulations, which showed only 11 gaps that were as large or larger than the observed gap. The authors thus concluded that the probability of finding such a void is $(2.2 \pm 0.7) \times 10^{-4}$.

A much simpler approach was taken by Srianand (1997), where lists of z values were generated for the observed redshift window. The distribution was assumed to be Poissonian because of the limited redshift interval under consideration. The approach taken here used the distributions in equation (7.6) instead, since it took advantage of the two Monte Carlo sets of 10,000 simulations that had already been created as described in section 8.5. The procedure is basically the one described by Rauch et al. (1992). The significance of the void was evaluated by first determining the distribution of maximum redshift intervals containing 0, 1, 2 and 3 lines. The redshift range that was considered was the same as in the spectrum of HE 0940–1050, spanning from $z = 2.4206$ to $z = 3.054$. In this first estimate, the column-density cut-off was chosen to match the detection limit of $\log N_{min} = 12.5$ that had been determined in section 9.2.

The lines in each of the $2 \times 10,000$ were first sorted according to redshift. A simple computer algorithm went through the list, searching for the maximum redshift interval between two consecutive lines as well as the largest redshift intervals containing 1, 2 and 3 lines. The largest gap sizes were recorded for each case. After all of the simulations had been processed in this way, a histogram was made of the maximum redshift intervals. Figure 9.2 shows the distributions of these maximum redshift intervals, plotted with a bin size of $\Delta z = 0.008$. It is reassuring to see that they have the same form as the analytical expression for the a priori probability distribution derived by Ostriker, Bajtlik and Duncan (1988).

The probability of such redshift gaps occurring by chance was then estimated by counting how many gaps of equal or greater size appeared in the 10,000 simulations for each model. The fact that the observed spectrum had the two small absorption lines

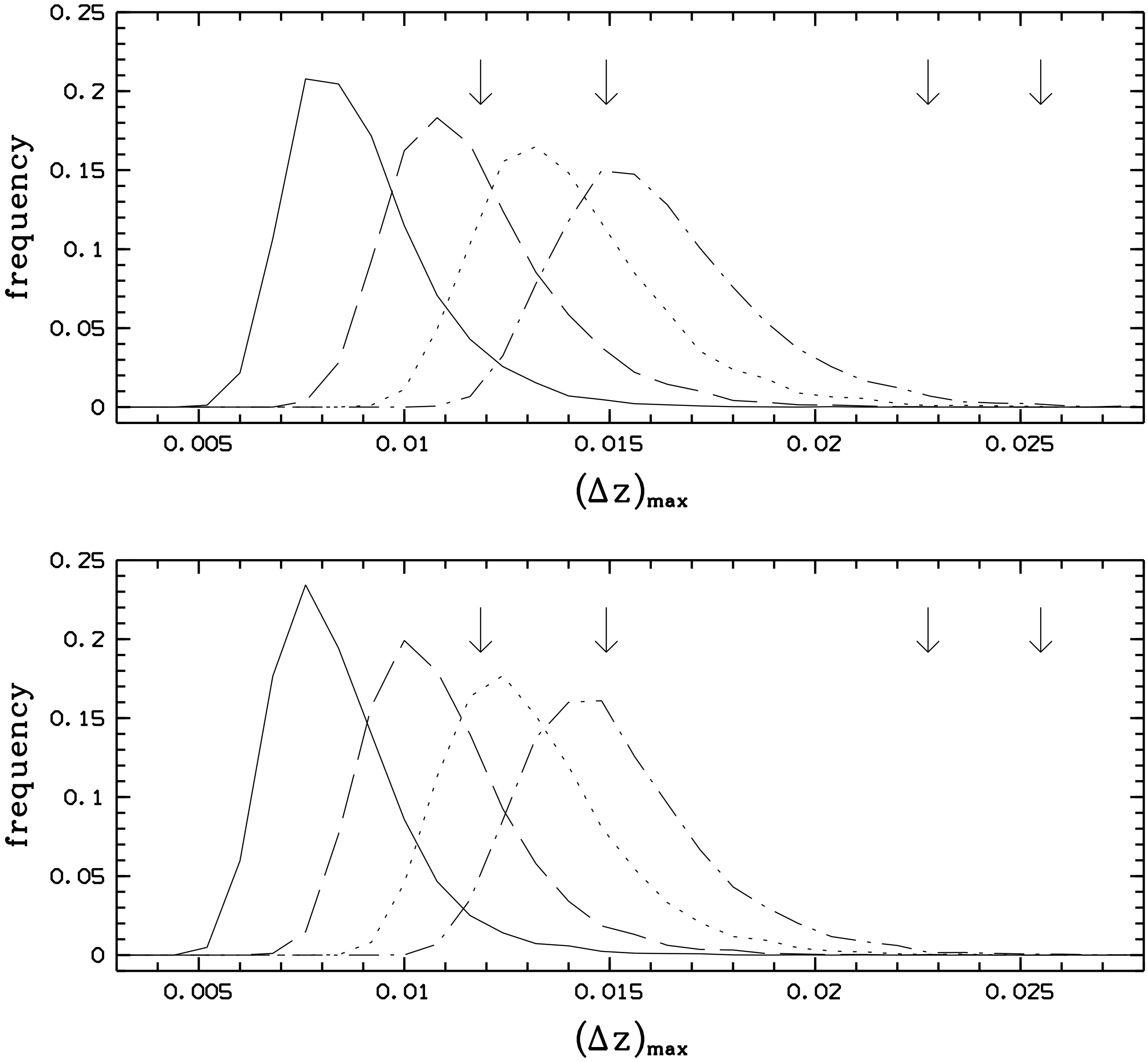

Figure 9.2: *Distribution of maximum redshift intervals containing 0, 1, 2 and 3 lines (curves from left to right), for* $\log N_{\rm HI} \geq 12.5$*. TOP: Model A1. BOTTOM: Model A3. The arrows indicate the sizes of the observed gaps toward HE 0940.*

Redshift interval	Number of lines	Probability (model A1)	Probability (model A3)
0.011858	0	6.40 %	3.62 %
0.014917	1	6.96 %	3.47 %
0.022745	2	0.32 %	0.12 %
0.025489	3	0.29 %	0.11 %

Table 9.2: *Probability of a larger redshift interval with 0, 1, 2 and 3 lines occurring by chance in 10,000 simulations for model A1 and A3, respectively.*

right in the middle of the void increased this probability greatly, since gaps roughly half of the full size of the void are relatively common: between 3% and 6%, judging from the results for models A3 and A1, respectively (see Table 9.3). However, some impression of the full void's significance can be gained by considering the z interval with two or three lines, where the probability of obtaining these two types of intervals by chance drops to 0.3% for model A1 and 0.1% for model A3. If Poisson statistics are used to determine the errors, the combined results from both models show that the probability of finding a void of this size with three lines is $(2.0 \pm 0.3) \times 10^{-3}$.

To be fair, it could be argued that a much higher cut-off of $\log N_{min} = 13.33$ would be more appropriate, given the incompleteness of the data at low column densities. In that case, the three small lines within the region would fall below this limit, as would the line on the right boundary. The saturated line to its right would thus become the new boundary of the possible void (now without any lines at all), so this time the computer algorithm searched for slightly larger redshift intervals of $\Delta z \geq 0.027576$ containing 0 lines. The resulting distributions are shown in Figure 9.3. In the 10,000 simulations for each model, the algorithm found 590 and 548 gaps of equal or greater size. The corresponding probability of finding such a gap by chance is between 5% and 6%, so from this point of view the void candidate appears insignificant, the mere result of statistical fluctuations.

The difference between the two estimates with different column-density cut-offs could be a reflection of the fact that such attempts to estimate the statistical significance of a void are extremely sensitive to very slight changes in the estimated line density (Dobrzycki and Bechtold 1991b). Scaling models A1 and A3 to match the line counts in the spectrum itself was in fact a form of estimating the line density. Since the void was included in this estimate, perhaps a new determination that excludes this part of the spectrum would yield a higher line density and thus a higher significance for the void—though this is debatable given the relatively small fraction of the spectrum that it represents.

The uncertainty seems to arise because of the difference between the detection limit and the estimated completeness limit in this spectrum.[2] While the second estimate of the void significance seems to indicate that the stronger lines show no particularly

[2]Unfortunately, no reference to either of these limits was found in the publications cited here.

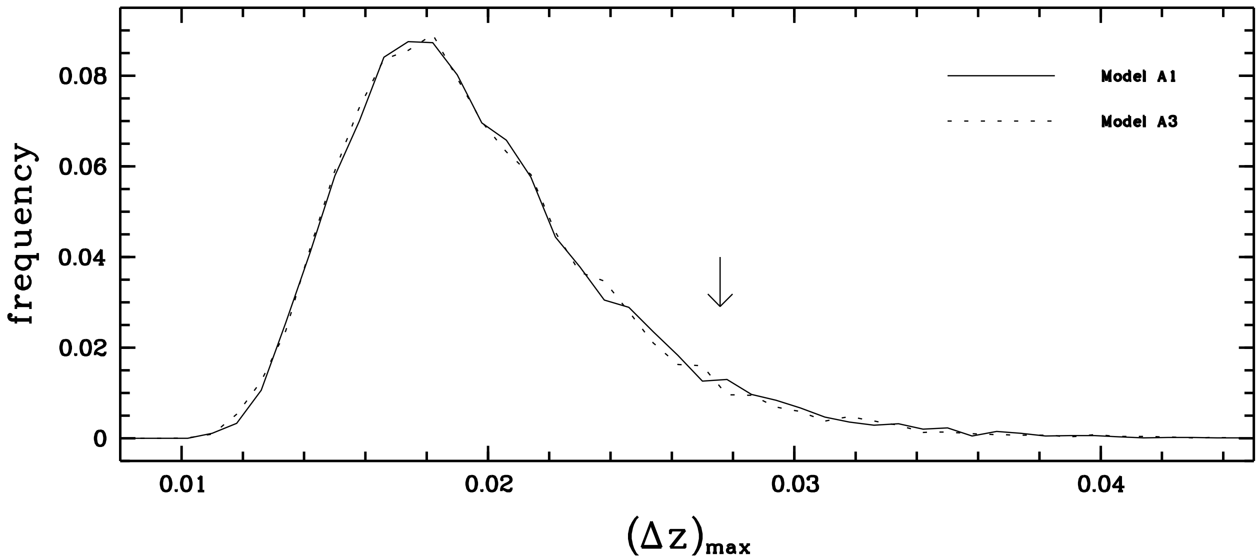

Figure 9.3: *Distribution of maximum redshift intervals between lines with* $\log N_{\rm HI} \geq$ **13.33**, *obtained from simulations of model A1 (dashed line) and A3 (solid line). The arrow indicates the size of the observed gap toward HE 0940.*

large gaps, the first estimate shows an apparent underdensity of weaker lines in the region around 4350 Å which is very clearly *not* due to any possible line blanketing.

9.4 Perspectives for a Foreground Quasar

Although the existence of a void has not been fully established, it is still interesting to consider what conditions would be necessary for identifying a foreground quasar responsible for causing it. The idea is plausible because the number density of weaker lines appears to be more strongly affected by quasar radiation than that of stronger lines (section 8.6), and the difference in the aforementioned significance levels for the void candidate could result from precisely such an effect.

If a foreground quasar does indeed exist, a few necessary conditions for observing it come to mind:

- First, the lifetime of the foreground quasar must be at least as great as the light-travel time to (the farthest part of) the void plus the time needed to ionize the Ly α clouds.
- Similarly, if a quasar begins to fade immediately after ionizing the clouds, it must survive at least as long as their recombination time in order to be observed together with the void; and even then it may not be recognized as having been bright enough to cause the void.

- Finally, if the quasar is radiating anisotropically, the energy must be emitted not only in the direction of the void but also towards Earth, so that it is not obscured from our line of sight.

So, assuming that such a quasar is causing an underdensity of lines in the spectrum of HE 0940, how bright or how close to the line of sight must it be? Combining equations (8.3) and (8.20) yields the condition for the foreground quasar's intrinsic Lyman-limit luminosity and its distance r_L from the void:

$$\left(\frac{L_{\nu_{LL}}}{4\pi\, {r_L}^2}\right) \quad \geq \quad 4\pi\, J_{\nu_{LL}} \cdot \omega_{min} \tag{9.2}$$

where ω_{min} indicates the ratio of QSO to UVB Lyman-limit flux densities at which the quasar's sphere of influence is considered to end. Inserting the proper units and writing $J_{\nu_{LL}} = J_{-21} \times 10^{-21}$ erg cm^{-2} s^{-1} Hz^{-1} sr^{-1} shows that the foreground quasar's sphere of influence extends out to a luminosity distance of

$$r_{max} \quad = \quad \left[\frac{1}{1.50\, J_{-21} \cdot \omega_{min}} \left(\frac{L_{\nu_{LL}}}{10^{30}\ \mathrm{erg\ s^{-1}\ Hz^{-1}}}\right)\right]^{1/2} \quad \mathrm{Mpc} \tag{9.3}$$

Bajtlik, Duncan and Ostriker (1988) consider a minimum ratio of $\omega_{min} = 0.1$ and conclude that the influence of a bright quasar ($L_{\nu_{LL}} \approx 3 \times 10^{31}$ erg s^{-1} Hz^{-1}) can affect a line of sight as far as 1° away on the sky. However, it makes more sense to argue that the column density of a typical Ly α forest line ($N_{\mathrm{HI}} \sim 10^{14}$ cm^{-2}) must be reduced by a factor of about 10 to make it undetectable (Dobrzycki and Bechtold 1991b). More reasonable values of $1 \leq \omega_{min} \leq 10$ thus correspond to distances of a few megaparsecs at most.

A few more calculations will show how these distances are related to angular separations on the sky. By definition of the angular size distance d_θ, the angle θ subtended on the sky by the proper length d_P at a distance is d_θ from Earth is $\theta = d_P/d_\theta$, where

$$d_\theta(z_x, z_y) = d_L(z_x, z_y) \cdot \left(\frac{1+z}{1+z_Q}\right)^2 \tag{9.4}$$

The angular size distance from Earth to the quasar is therefore

$$r_\theta \quad = \quad d_\theta(0, z_Q) \quad = \quad \frac{r_Q}{(1+z_Q)^2} \quad = \quad \frac{2c}{H_o}\left[\frac{\sqrt{1+z_Q} - 1}{(1+z_Q)^{3/2}}\right] \tag{9.5}$$

for $\Omega_o = 1$ (Kayser et al. 1997). Assuming that the possible foreground quasar has the same redshift $z_Q \approx 2.580$ as the void candidate, this is a distance of $r_\theta = 790h^{-1}$ Mpc. Because the distance to the foreground quasar is much greater than the distance between the quasar and the void, the luminosity distance r_{max} is basically the same as the proper distance d_P and the angle subtended on the sky becomes

$$\theta \;\approx\; \frac{r_{max}}{r_\theta}. \tag{9.6}$$

Equations (9.3), (9.5) and (9.6) can be combined to obtain the direct relation between ω, $L_{\nu_{LL}}$ and θ:

$$L_{\nu_{LL}} = c_1 \ \omega_{min} \, J_{-21} \ \frac{\theta^2 \, {r_{_Q}}^2}{(1+z_{_Q})^4} \tag{9.7}$$

where $c_1 = 1.50 \times 10^{30}$ erg s^{-1} Hz^{-1} Mpc^{-2}. Figure 9.4 makes use of this relation to show the angular extent on the sky of the possible quasar's sphere of influence for different values of ω. Logically and as seen on the scale of the y-axis, such a zone of enhanced ionization is larger for lower estimates of the UVB Lyman-limit intensity. However, roughly speaking, even a bright source would probably have to be within 10′ (minutes of arc) on the sky, while a faint but closeby UV source could produce the same effect.

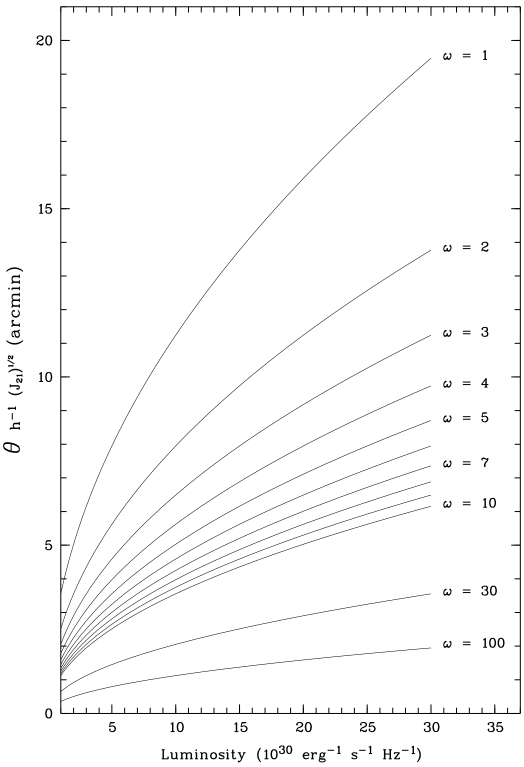

Figure 9.4: *Angular extent of enhanced ionization around a hypothetical foreground quasar with* $z_{_Q} \approx 2.580$.

In order to calculate the range of B magnitudes for the possible foreground quasar, the equations derived in sections 8.2 and 8.3 were first used to obtain the flux observed at $\lambda_{obs} = 4400$ Å for a given Lyman-limit luminosity $L_{\nu_{LL}}$:

$$f_{\lambda_{obs}} = \frac{c}{\lambda_{obs}} \frac{1+z_{_Q}}{4\pi {r_{_Q}}^2} \left[\frac{\lambda_{LL}(1+z_{_Q})}{\lambda_{obs}} \right]^{\alpha} L_{\nu_{LL}} \tag{9.8}$$

Combining this with equation (9.7) and the standard units resulted in the condition

$$f_{\lambda_{obs}} = c_2 \; \frac{{\lambda_{LL}}^{\alpha}}{{\lambda_{obs}}^{2+\alpha}} \; (1 + z_{Q})^{\alpha-3} \;\; \omega_{min} \, J_{-21} \, \theta^2 \tag{9.9}$$

where $c_2 = 0.0376$ erg cm^{-2} s^{-1} Å. The B magnitude could then be obtained with the help of the following formula (Weedman 1986):

$$B = -2.5 \log f_{4400} - 20.42 \tag{9.10}$$

where f_{4400} is the flux density in erg cm^{-2} s^{-1} Å^{-1} at $\lambda_{obs} = 4400$ Å.

Assuming a spectral index of $\alpha = -1$ for convenience, Figure 9.5 shows the B magnitude as a function of the angular separation θ on the sky for different values of ω and J_{-21}. For separations of only a few minutes of arc, the magnitude of the foreground quasar is not strongly constrained and even weak sources could ionize the hydrogen strongly along the line of sight to quasar HE 0940–1050.

Obviously, then, it would be worth searching for the quasar that might have caused the void candidate described above (and not only because it would lend credence to the assertion that the feature is probably significant). Of the two confirmed voids in the literature, one foreground quasar has been found at the same redshift as the void, while the other has been found at a higher redshift. As Srianand (1997) has noted, the detection of a quasar with a slightly lower redshift than the observed void would lend support to anisotropic models of quasar radiation. And in the very worst case, even a negative result of the search for a foreground quasar could provide an additional data point for further studies of quasar anisotropy, variability, and lifetimes.

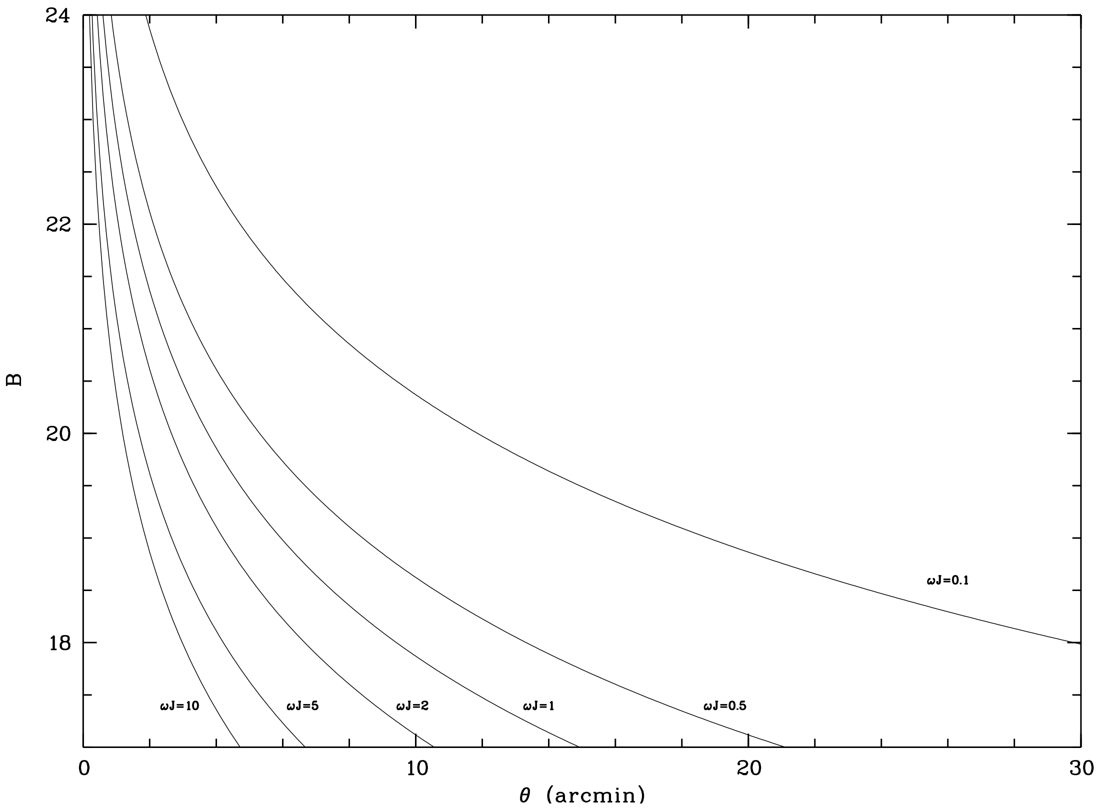

Figure 9.5: *B magnitude vs. angular separation from line of sight to HE 0940–1050 for a foreground quasar with* $z_Q \approx 2.580$.