# LIMITS ON THE NUMBER OF CLOSE OPTICAL QUASAR PAIRS

D.W. WEEDMAN
Department of Astronomy, The Pennsylvania State University, University Park, Pennsylvania 16802

S. DJORGOVSKI
Astronomy Department, California Institute of Technology, Pasadena, California 91125

ABSTRACT A new search has been conducted for close pairs of quasars with identical spectra, including both emission line objects and blue stellar objects. Survey plates covering 3.9 $deg^2$ were selected for image quality, full image widths being 0".8 to 1".2. Although 200 to 400 quasar spectral images should have been examined, no candidate pairs with separations < 4" were found. Eight such pairs from 4" to 10" were found, but none were subsequently confirmed as lensed quasars. The selection bias is derived and applied to these limits. It is concluded that the absence of close pairs expected from gravitational lensing models cannot be explained by observational selection effects.

## INTRODUCTION

Given the pressing mystery of how dark matter is distributed in the universe, any tool with potential for revealing this matter is eagerly seized upon. This explains why the theory of gravitational lenses has been considered so rapidly and thoroughly even though only a few lenses have as yet been observed. The study of Turner, Ostriker and Gott (1984) demonstrates that predicting the observable properties of lensed quasars is a complex effort, incorporating many astronomical assumptions, but testable predictions are made. The primary parameter that distinguishes predictions is the relative significance of isolated lenses, such as individual galaxies, compared to distributed lenses, such as galaxies in clusters. Essentially, lensing models that rely primarily on individual galaxies predict smaller separations of lensed quasars than models dominated by clusters.

Median separations of lensed quasar images vary from 1"

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to 4" among the models of Turner et al. Unfortunately, this is also a range for which discovery bias, for optically observed quasars, is difficult to evaluate. In comparing the predictions with existing observations, only one anomaly is conspicuous. This is the wider separations found for lensed pairs than expected from the models. It is tempting to attribute this anomaly to selection effects which have entered the observations. In the present paper, we consider a selected sample of the highest quality optical survey plates in an attempt to improve the search for close pairs and evaluate the selection bias. The conclusions emphasize that important things can be learned even from upper limits, and we encourage quasar surveyors to undertake similar tests with their own data.

## OBSERVATIONS

Two lensed quasars have already been found serendipitously in searches of low dispersion spectroscopic survey plates (Weedman et al. 1982, Djorgovski and Spinrad 1984). These plates were obtained with large telescopes (the 3.6-m Canada-France-Hawaii Telescope (CFHT) and the 4-m at Kitt Peak National Observatory) for the purpose of seeking quasars at high redshifts by finding objects with conspicuous Ly $\alpha$ emission. The two lensed quasars were of a sample of 151 emission line quasars published in two surveys (Sramek and Weedman 1978, Gaston 1983). Only quasars with detected emission lines have so far been published in such surveys, even though there are probably many more quasars on the plates showing only continuous spectra. (Primarily, these plates are able to detect only Ly $\alpha$ and sometimes CIV $\lambda$1550 or CIII]$\lambda$1909 emission. Quasars at redshifts such that these lines were not present would not show emission lines). The best of such survey plates have been obtained with the "grens" on the CFHT. A plate such as that on which was found the lensed pair 2345+007 typically shows 20 to 25 emission line quasars and over 100 objects with blue continua, or blue stellar objects (BSOs), many of which are probably quasars. The BSOs are not reported as candidates because, being faint and without strong emission lines, follow-up confirmations would be very laborious and so probably never done.

Nevertheless, the BSOs on the plates are a potential source of new lensed pairs. The BSOs taken with the emission line quasars provide an upper limit to the possible quasars present, so provide useful limits to the relative fraction of quasars that show detectable lensed images. Consequently, DWW selected the seven best plates obtained with the CFHT, all previously examined for emission line quasars, and searched them again for close pairs with any kind of similar spectra.

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No spectroscopic criterion was applied other than the rejection of spectra with absorption features classifying them as stars. In practice, only blue objects show featureless spectra, although many of the BSOs really are blue stars. The plates examined, listed in Table I, were selected as having images with full width perpendicular to the dispersion of < 1.2". On

TABLE I Survey Fields Examined

| CFHT Plate No. | UT Date (mo/day/yr) | Field Center RA (1950) | Dec. | Spectral Width |
|---|---|---|---|---|
| 1421[1] | 8/03/81 | $16^h33^m20^s$ | +33°42' | 1".1 |
| 1424[2] | 8/03/81 | $23^h41^m48^s$ | +01°03' | 1".1 |
| 1425[2] | 8/03/81 | $23^h46^m20^s$ | +00°24' | 1".2 |
| 1426[2] | 8/03/81 | $00^h02^m23^s$ | -00°57' | 1".2 |
| 3030[1] | 1/09/83 | $08^h41^m40^s$ | +44°44' | 1".2 |
| 3044[1] | 1/10/83 | $12^h57^m25^s$ | +35°37' | 1".0 |
| 3435[1] | 6/16/83 | $13^h09^m35^s$ | +28°27' | 0".8 |

1. Emission-line quasars discovered on this plate are in Weedman (1985).
2. Emission-line quasars discovered on this plate have been published by Gaston (1983).

the best plate, this width was 0.8". (An image is illustrated by Weedman et al. 1982). These plates, therefore, represent those with the best seeing and are about as good as achievable with existing survey techniques. In this search for pairs, an upper limit of 10" separation was adopted for listing objects as possible lensed pairs. Visual inspection was the only criterion for judging if objects have identical spectra, and in the spirit of providing upper limits, this criterion was not overly strict. All possible new candidates for lensed pairs are given in Table II. The total area surveyed by the seven plates is 3.9 $deg^2$.

CCD images and spectra for all candidates except pair #1 were obtained by SD using the 3-m telescope at Lick Observatory. All candidates observed are stars, except that the fainter of pair 4 is a quasar with a single emission line at 5150 Å, and the fainter of pair 6 may have weak emission lines. In no case was a lensed pair confirmed. This strengthens the upper limit to possible pairs in this survey.

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TABLE II Quasar Pair Candidates[1]

| No. | Position R.A. (1950) | Dec. | Mag. Brighter | Mag. Fainter | Companion Location | |
|---|---|---|---|---|---|---|
| 1 | $00^h02^m03^s.2$ | -00°48'31" | 18 | 20 | 9" | N |
| 2 | $16^h33^m56^s.7$ | +33°30'27" | 17.5 | 21 | 7" | SW |
| 3 | $16^h34^m11^s.3$ | +33°25'36" | 19 | 19 | 9" | W |
| 4[2] | $16^h34^m21^s.5$ | +33°22'00" | 20 | 22 | 7".5 | N |
| 5 | $23^h41^m08^s.5$ | +00°53'22" | 20 | 20 | 4" | NW |
| 6 | $23^h44^m52^s.2$ | +00°15'20" | 19.5 | 20.5 | 5" | NW |
| 7 | $23^h46^m38^s.5$ | +00°22'16" | 19.5 | 20 | 7" | SE |
| 8 | $23^h47^m44^s.3$ | +00°38'42" | 19 | 19.5 | 9".5 | N |

1. Positions, given for brighter component, were determined from spectra on the survey plates, relative to two SAO stars on a typical plate. Listed positions may be uncertain up to ± 10".
2. All other candidates listed are blue stellar objects. This one is an emission line quasar with what appears to be another image of the emission line, displaced 7".5 N. Continuum of this companion is very weak.

## DISCUSSION AND CONCLUSIONS

What we wish to know, for comparison with models, is the fraction of quasars that appear paired as a function of separation. Fortunately, Turner et al. (1984) showed that the magnitude limit of the quasar sample is not particularly important; all that is really necessary is to know the total number of quasars examined. Translating the upper limits for the number of pairs in Table II into percentages of quasars then requires only knowing the total number of quasars that were examined on these plates, regardless of whether we knew they were actually quasars.

Sufficient quasar counts have been made that the number of quasars $deg^{-2}$ brighter than a given magnitude is reasonably well known. A good summary is given by Braccesi (1983). If we know the limiting magnitude of the present survey, the published counts allow a determination of how many quasars are included in the fields examined. Available calibration of the plates indicates that they are complete close to blue continuum magnitude 21, for detecting continuous spectra in addition to emission lines. Gaston (1983) used microdensitometry and the signal to noise ratio of the spectra traced to conclude that the continuum magnitude limit for emission-line quasars

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is 21.1 ± 0.3 mag on three of the plates used. DWW attempted another calibration based only upon objects with continuous spectra. A CCD image was obtained by W.C. Keel with the 4-m telescope at Cerro Tololo Inter-American Observatory for a small area in the vicinity of quasar 0003-010 listed by Gaston. Fifteen faint objects were identified on the survey plate for which Keel subsequently determined the V magnitudes from the CCD image. We concluded from this comparison that the plate was complete to magnitude 20.5 and 50% to 75% complete at mag. 21. As the objects used for this test were redder than quasars (being stars and galaxies), the B magnitudes that determine detectability on the plates would actually be fainter than the V magnitudes given. It is reasonable to assume, therefore, that the limit in B magnitude for the search described in the present paper is somewhere between 20.5 and 21 mag.

From the tabulation by Braccesi (1983), this range of B magnitude gives from 50 to 80 quasars $deg^{-2}$ expected. As the survey encompassed 3.9 $deg^2$, from 200 to 300 quasars should have been examined. In fact, 140 emission line quasars had already been noted on the plates. Many of these have continuum magnitudes fainter than the listed limit (Gaston 1983), so can be considered as extra quasars sampled for pairs. A generous range of uncertainty would be that from 200 to 400 quasars have been examined for pairs in the new survey reported in the present paper.

The most important result is that of all these quasars, none are found in pairs with separations less than 4". It is then necessary to decide what is the selection bias for detecting separations of this order or smaller. Even though image sizes are 1.2" or less, even smaller separations could be detected by the blended but widened spectra produced by a pair. When searching such plates, images are continuously compared with nearby spectra of stars so even slightly widened spectra are noticed. Similarly widened spectra could also be produced by barely resolved galaxies, however. For this reason, we have determined a conservative selection bias function for each plate using the criterion that an image pair would be noted if the blended spectrum of the pair had a width twice that of a single spectrum. In this circumstance, two distinct image cores would be seen. This criterion is equivalent to requiring the component of separation perpendicular to dispersion equal or exceed the normal image width. Using widths from Table I folded with a random distribution of position angles for pairs, this selection bias weighted for the total of seven survey plates is as given in Table III.

Limits on the fraction of quasars found as close pairs can now be considered. Using the selection bias applied to from 200 to 400 quasars (the sample uncertainty), a pair with separation of 1".8 or greater, for example, should have been

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TABLE III Selection Bias for this Survey

| Pair Separation | Percent Detectable |
|---|---|
| 0.″8 | 0 |
| 0.″9 | 4.3 |
| 1.″0 | 5.8 |
| 1.″1 | 11 |
| 1.″2 | 20 |
| 1.″3 | 36 |
| 1.″4 | 42 |
| 1.″5 | 48 |
| 1.″6 | 52 |
| 1.″8 | 59 |
| 2.″0 | 64 |
| 2.″2 | 67 |
| 2.″4 | 70 |
| 3.″0 | 76 |
| 4.″0 | 83 |
| 5.″0 | 86 |
| 6.″0 | 88 |
| 8.″0 | 91 |
| 10.″0 | 93 |

found if such pairs occur in 0.4% to 0.8% of quasars. The absence of such a pair is consistent with the quantitative predictions of Turner et al.; their "standard" model for $q_o = 0$ predicts that 0.5% of quasars should be found as pairs with median separation 1.75", or 0.25% with separations greater than this. They point out that this prediction is actually a lower limit, conceivably by a large factor, because it neglects the basic flux amplification bias and includes only the mass distribution in known objects. Yet the observational limit indicates that this prediction is not greatly underestimated.

With the improved resolution, the absence of close pair candidates remains surprising compared to the two wide pairs (7.3", 3.8") already found in identical surveys. These two were from a total sample of 151 emission line quasars (Sramek and Weedman 1978, Gaston 1983), yielding a literal fraction of 1.3% for separations $\gtrsim$ 4". Using the predictions of Turner et al. (their Figure 11), three times as many pairs are expected for separations > 1.″8 compared to > 4". For a sample of 200 to 400 quasars and the selection bias in Table III, 5 to 10 new pairs would have been expected, naively scaling by the wider pairs already found. Meaningful statistical conclusions

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cannot be drawn from the small sample of pairs currently known, but the fact that disagreement approaches an order of magnitude demonstrates the puzzle that exists. This demonstrates why continued examination of optical quasar survey plates to locate any possible examples of lensed pairs is extremely important, even if results can only be expressed as limits. It also demonstrates the need for further careful studies of existing wide pairs, to confirm that they are indeed lensed objects rather than truely binary quasars (e.g. Djorgovski et al. 1987).

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