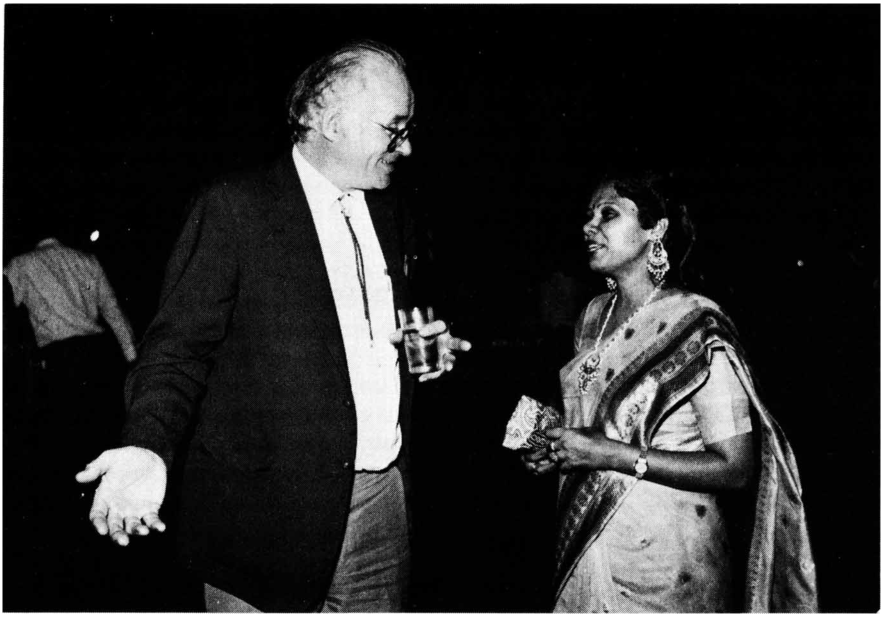
VI

QUASARS AS PROBES OF THE INTERVENING MEDIUM

"The evidence is now at hand to show that the lensing phenomenon is common enough to be a reasonable subject of study and not just a curiosity."

\- Bernard Burke (p.525)



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GRAVITATIONAL LENSES: OBSERVATIONS

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ABSTRACT: The gravitational lens phenomenon is shown to be not uncommon. A search is now underway to find a larger number of examples, using the VLA to search for candidates, following up with optical observations to establish equality of redshifts in the images. Most of the present lensing examples exhibit anomalous behavior that is most easily understood as evidence for large quantities of intervening non-luminous matter.

1. PROPERTIES OF GRAVITATIONAL LENSES

In 1919, Sir Arthur Eddington led an eclipse expedition to verify Einstein's prediction of the deflection of starlight by the sun's gravitational field. In the years that followed, it was widely recognized that the effect was an optical one, and could be observed, in principle, on an interstellar scale. Eddington (1923) and Einstein (1936) both recognized that magnification and multiple-imaging of a distant star by a foreground star was improbable, but Zwicky (1937) recognized that the effect might be observable in an extragalactic context. He proposed that the images of compact N-type galaxies might be significantly modified by foreground galaxies, and he proposed that the effect, being solely gravitational, could be a new tool for studying the distribution of matter in galaxies.

The discovery of quasars revived the discussion [see Greenfield _et al_ (1985) for historical references], and the predictions were confirmed when Walsh, Carswell, and Weymann discovered that the radio source 0957+561 was double, and displayed the characteristics of a multiply-imaged quasar. The two quasar images were separated by 6", and were designated A and B (B being southernmost), with both having similar spectra and equal redshifts. After some puzzles raised initially by radio and infrared observations [Greenfield _et al_ (1979) Walsh _et al_ (1979)] the central issues were resolved by the observations of Stockton (1980) and Young _et al_ (1980) who showed that there was a foreground cluster of galaxies, and that the brightest member was a giant cD galaxy only 1" north of the southern image. Any reasonable model of that galaxy would predict multiple images of some sort, given

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the proximity of the B image. The major surprise, as demonstrated by Young et al (1981) and by Greenfield et al (1985), was the inadequacy of interpreting the imaging in terms of conventional Mass-to-Luminosity ratios for the visible matter. A substantial quantity of dark matter, presumably associated with the cluster as a whole, has to be invoked to explain the observations.

The idealized cases of a point mass and a singular isothermal sphere have been treated by a number of authors (e.g. see the review by Peacock, 1983), and these illustrate the scale of the phenomenon. If there is a 10^{12} $M_\odot$ point-mass lens at 1.5 Gpc, a quasar at 3 Gpc, and one assumes Euclidean geometry, then $r_o = 2''$ in the point-mass case; for the isothermal sphere, with $\sigma_v = 300$ km/s, $r_o = 0''\!.4$. More realistic cases show a greater complexity of images. Bourassa and Kantowski (1975) treated ellipsoidal mass distributions and showed that a variety of caustic surfaces between singly-imaged, triply-imaged, and quintuply-imaged domains existed, and a wide variety of investigations have been carried out since then. The orders of magnitude of the lensing effects remain the same as in the simple cases but the complexity is substantial.

2. THE OBSERVATIONAL STATUS

Both intrinsic and extrinsic astrophysical uses can be expected from gravitational lens observations. One intrinsic interest derives from the magnification itself: since the magnification can be substantial - of the order of 100 in some cases - greater angular resolution is achieved, an advantage that should be of particular interest for VLBI observations at radio wavelengths, and for HST observations at optical wavelengths. Another application has already been noted by Gott and Gunn (1974) before the lensing phenomenon had been established; they considered 1548+115, an accidental quasar pair, which allows one to probe the distribution of matter in the closer quasar by looking for extra images. Finally, there is the potential problem that might arise if distant quasars have a high probability of being lensed. In such a case, the high luminosity, high redshift part of the luminosity function might be subject to correction. In order to check the importance of such corrections, Roberts, Turner, Gott, and Burke (unpublished) used the VLA to examine twenty-five high-luminosity quasars, all having absolute B-magnitude -29 or brighter, looking for the multiple images that might be expected if lensing were a frequent occurrence in the sample. The results were largely negative: only one quasar in the sample showed evidence of structure that might be due to lensing, and that example is marginal. They concluded that lensing does not make an important perturbation to the observed quasar luminosity function.

The extrinsic uses of gravitationally lensed quasars have received the most attention, since the phenomenon, being purely gravitational is an informative probe of the intervening matter in the universe. In the case of 2237+050, discovered by Huchra et al (1985), one is probing the matter distribution close to the center of a nearby galaxy, but the other lens cases, as will be seen, probe both galactic and cluster mass distributions, with strong evidence for the presence of substantial quantities of dark matter. The large-scale matter distribution in the universe may also have an observable effect and one must stay alert to more exotic possibilities such as strings and black holes. An even more extreme conjecture, the existence of a "shadow universe" observable only through the gravitational interaction, has been raised by recent speculations in particle theory, and such a presence would probably be manifest primarily through lensing effects.

There are now seven cases of lensing known. Their principal properties are summarized in Table I, which shows the principal features as they were known in December 1985. The maximum separation between components is given in Column (2), the flux ratio of the two brightest components is given in Column (3) with 1115+080 being a special case. The redshifts of quasar and lens appear in Columns (4) and (5). The character of the visible lens (if any) is given in (6): galaxy (G), cluster (C), galaxy plus cluster (B) or no visible candidate (N). Column (7) indicates radio-loud cases and the number of detected quasar images is shown in Column (8).

TABLE I

Object	$D_{max}(\pi)$	S_A/S_B	Z_Q	Z_L	Lens	Radio?	No. Images
0957+561	6.1	3,1	1.41	0.39	B	Yes	2
1115+080	2.7	1.1*	1.72	--	G?	No	4
2345+007	7.3	4.0	2.15	--	N	No	2
2016+112	3.4	1.6	3.27	1.0	G,G;No C	Yes	3
1635+267	3.8	4.4	1.96	--	N	No	2
2237+050	2.2	?	1.70	0.04	G	No	2
0023+171	4.8	2.5	0.95	--	N	Yes	2

*Image A is actually double, with nearly equal fluxes for A_1 and A_2.

Three immediate problems are raised by the data of Table I: the rarity of odd images, the wide spacing between components, and the frequency with which the "N" designation appears in the "Lens" column. Only one of the seven cases exhibits an odd number of proven images, contrary to expectation. This problem may be more apparent than real, since a lens with a compact central component will generally exhibit one faint image that might easily be below the level of detectability, since a compact central mass approximates a singularity. The wide spacing, always greater than an arc-second, is also surprising, especially in view of the model studies of Turner et al (1984), who showed that conventional assumptions concerning cosmology and the structure of galaxies would lead one to expect a preponderance of multiple images in the half-to-one arc-second range. Observational selection may account for the failure to see this class of object more frequently; 2237+050 is the only present example, but represents an unlikely coincidence, discovered fortuitously. A systematic search for multiply-imaged quasars, with image separation of the order of 0.5 to 2 arc-seconds, is urgently needed.

The final puzzle, the relative frequency with which no visible lens appears, is an awkward and unexplained anomaly. The most straightforward interpretation is that dark matter is playing an important role, either in the form of under-luminous galaxies or clusters, or in the form of intrinsically dark aggregations of matter, perhaps of novel character.

The position and flux density of the observed images are the principal observables at any given time, but since quasars are frequently time-variable, there is a further class of interesting phenomenon: the relative time delay in the time-series of the flux for each image. A value for the relative time delay between the A and B images in 0957+561 has been published by Florentin-Nielson (1984), but the data were too incomplete to be convincing. More complete measurements will be awaited eagerly. The interpretation, as pointed out by Alcock (1985), is interesting: the Hubble constant and the deceleration parameter are not determined reliably, despite one's naive expectations, because fluctuations in the matter distribution of the universe can cause major perturbations even if the lens model is correct. Instead, one can take advantage of this sensitivity; if the Hubble constant can be determined with precision by luminosity-distance methods, the time delay in the lens cases will then give a quantitative measurement of matter fluctuations in the universe. If a sufficiently large number of examples can be measured, the method is also an effective way of measuring the cosmological constant Λ_o.

3. SEARCHING FOR NEW GRAVITATIONAL LENSES

In astrophysics, nearly all observable phenomenon are complex, and only rarely, if ever, does a single example provide deep understanding. The Hertzsprung-Russell diagram and the Hubble classification scheme for galaxies come to mind as instances in which the order underlying a phenomenon could never have been demonstrated with a handful of objects. Similarly, it is clear that gravitational lensing is a rich but complex phenomenon that can be understood and used best if a substantial number of examples can be found. Both radio and optical searches should be carried out. Expectations can be estimated from the present data base. Six examples (the seventh, 2237+050, is exceptional) were recognized by their multiple character, and all were drawn from reasonably well-defined samples. There were 486 quasars in the optically-defined samples; the radio samples include both quasars and radio galaxies, but for estimating the occurrence of lensing, they are sufficiently well-defined: about 600 quasars would be found in the radio samples. This accounting, however, neglects the negative searches, and this number is more difficult to determine. Private communications from B. and D. Wills and from E.M. Burbidge give negative results from samples of 250 and 320 quasars, respectively; both groups would surely have seen multiples having spacings of 2 arc-seconds or greater. Most other negative searches seem to be incomplete at this stage, and one can conclude, therefore, that six multiply-imaged quasars have been found in a total sample size of about 1700. The incidence of multiple imaging, therefore, can be expected to be about 1 in 300, for high redshift quasars.

A radio search for more examples of lensing has been in progress for the past few years. The principals in the work have been J. Hewitt, C. Lawrence, E. Turner, and B. Burke, although much wider help has come from other colleagues at Princeton and CalTech. The strategy starts with the raw material of the MIT-Green Bank 300-foot telescope source study (the MG Survey, Bennett et al 1986); the VLA is used in the snapshot mode to obtain accurate position and source structure, using the methods described by Lawrence et al 1984). All sources that show multiple, compact structure, except for the obvious cases of double-lobed radio galaxies, are identified as potential candidates (about one out of ten sources qualify). Next, optical continuum images are taken, most commonly by the Kitt Peak 4m telescope, and if there is evidence of multiple optical structure, the source becomes a candidate for spectroscopic examination (about one in ten of the first-cut candidates, or one in a hundred of the original sources, meets this criterion). Finally, spectra are taken, usually with either the Kitt Peak 4m telescope or the Palomar 5m telescope. If the images have identical spectra and redshifts, this is taken as strong evidence for lensing. Once in a while, one might accidentally be misled by a galaxy with multiple active nuclei, but this should not be a common occurrence. The snapshot material now includes 3000 sources, and we hope to add another 2000 to the list in the upcoming observing season with the VLA; one might expect, therefore, between ten and thirty new lens examples when the search is complete. An examination of the first 1000 snapshots is now nearing completion. The snapshots should be a valuable resource for other projects, and will be made available to the astronomical community.

4. THE RADIO-QUIET CASES

Four of the seven examples of lenses in Table I are undetectable at radio frequencies, or at any rate have fluxes that are below 50 μJy [Greenfield, Roberts, and Burke, unpublished; Huchra et al (1985)]. As noted above, 2237+050 is a fortunate alignment of a nucleus of a nearby galaxy with a distant quasar, and Tyson has reported detection of a pair of images, plus the nucleus of the galaxy, at this meeting. Two of the examples, 1635+267 (Djorgowski and Spinrad, 1984) and 2345+007 (Weedman et al 1982), despite the large spacing between images, are lacking visible foreground matter that could serve as a lens. The fourth, 1115+080, discovered by Weymann et al (1980), was originally reported to be triple. Young (1981) predicted that it should be quintuple, with the A image split into two components; the fifth image would be faint. The lensing material would be an edge-on spiral, roughly parallel to A_1 and A_2 and situated between these and the B and C images. Hege (1981) showed by speckle interferometry that the A image was, indeed, double. Reports of detection of a foreground galaxy have been indecisive, but a recent image, taken by Wlérick and his collaborators with the Mauna Kea CFHT, provides clear evidence that there is no foreground edge-on galaxy at the position predicted by Young. Whether a galaxy image is merged with the A_1 and A_2 images is not yet established; the observational proof will not be easy, but is an intensely interesting result that one hopes will be forthcoming soon (a preprint by P. Henry presents evidence for such a galaxy).

5. THE RADIO-LOUD CASES

5.1 0957+561

When a gravitationally lensed quasar is radio-loud, there is usually a larger set of observable quantities that place more stringent limits on acceptable lensing models. This, the original example of a multiply-imaged quasar, provides an illustrative case. A summary of the radio observation with the VLA has been given by Greenfield et al (1985)and Roberts et al (1985); the optical data has been summarized by Young et al (1981). A recent map is given in Figure 1, showing the A and B images, coincident with the optical quasar images, the G image, nearly coincident with the galaxy G1 that is the brightest member of the foreground cluster, and the jet-like structures to the NE and SW of A that, for the most part, are singly imaged. There are a large number of constraints, and Young et al (1981) proposed using a double-ellipsoid model that, despite the large number of free parameters, does not allow arbitrary freedom in choosing models. The VLBI data of Porcas et al (1984), Gorenstein et al (1983), Cohen (1984), and Bonometti (1985) give convincing proof of the general lens properties. Both the A and B images have jet-like structures extending approximately 50 mas in nearly the same position angle, and Bonometti's work showed that these jets each have a spur to one side that exhibits the proper reflection symmetry predicted by the two-ellipsoid model. In addition, each core shows a small sub-jet of the order of 0.6 mas length. If these were moving, the difference in time delay for the two patterns would result in their presenting different aspects at a given instant. As it turns out, the motions appear to be slow, and the relative values for all components of the magnification matrix can thus be derived from observation of the small jets, and independently from the larger (50 mas) jets.

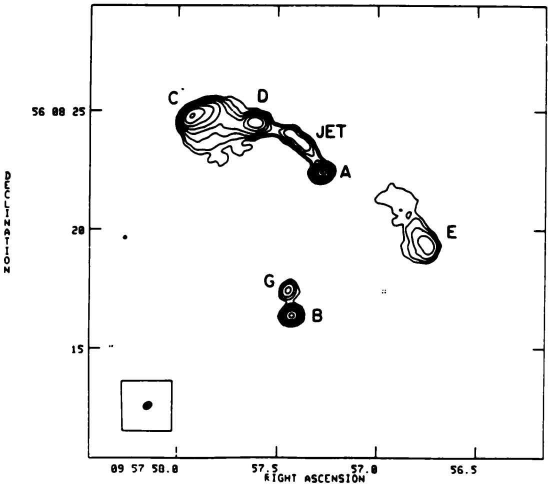

Figure 1. VLA λ6 cm Map of 0957+561, December 1980

Bonometti gives relative magnifications of 1.236±.007 and -0.46±.01 for the major and minor axes, and position angles of 18°.75±°.06 and 98°±4°. The model values are close to these: Greenfield *et al* (1985) and Higgs (1984) derived similar double-ellipsoid models that reproduced the data reasonably well.

The observational work to date has established a number of physical facts for 0957+561:

1) No single value of mass-to-luminosity for the foreground cluster of galaxies gives a lens that fits the data, nor does a quadratic law of the form $M = aL + bL^2$.

2) The double-ellipsoid model of the type introduced by Young *et al* fits the data, but not uniquely. One ellipsoid is centered on the galaxy; the second, more massive ellipsoid is centered to the Southwest approximately 10" from the B image. A large quantity of dark matter, matter not associated with the visible galaxies, is implied by this model.

3) No third image has yet been identified. The models predict that it should be faint, and close to the nucleus of galaxy G1. Gorenstein *et al* (1983) found a compact VLBI image not far from the center of the radio source G, but their later work (cf. Bonometti) indicates that this is probably not the third image. The G source is extended in the VLA maps, and may have nuclear structure of its own.

4) The forms of the 50 mas jets demonstrate further that gravitational lensing is the definitive explanation for this object.

It is clear that the models are not unique. Falco, Gorenstein, and Shapiro (1985) show that, for any two images, the positions, relative magnification, and difference in propagation time are unchanged under a simple transformation of the mass distribution (generalizations by Gorenstein *et al* and Falco *et al* are in preparation). Nevertheless, it is clear from their work that anomalous mass distributions, not related to conventional visible matter, must still be invoked. Radio observations, which impose more restraints, are useful in restricting the allowable models.

5.2 2016+112

The gravitational lens 2016+112, described by Lawrence *et al* (1984) and Schneider *et al* (1986) consists of a triple radio structure (Figure 2), with the two upper sources, A and B, being separated by 3".4. These are coincident with faint quasar-like optical objects that exhibit sharp emission lines with identical redshifts of 3.273. The southern radio source, C, is slightly extended. Optically, a faint galaxy D is seen 1".2 from B, in addition to a coupled at C consisting of both a galaxy and a third quasar image [Schneider *et al* (1986), in preparation]. The galaxy D, in this recent work, exhibits a spectrum that matches closely the spectrum of a giant elliptical galaxy when corrected for redshift, and shows evidence of an H and K absorption break at z = 1.01, probably the largest absorption-line redshift yet. The recent optical work of Schneider *et al* also shows that there are two faint emission patches NW of A and B. These are shown in Figure 3, which shows a pair of photographs taken with the "PFUEI" camera on the Palomar 5m telescope. The

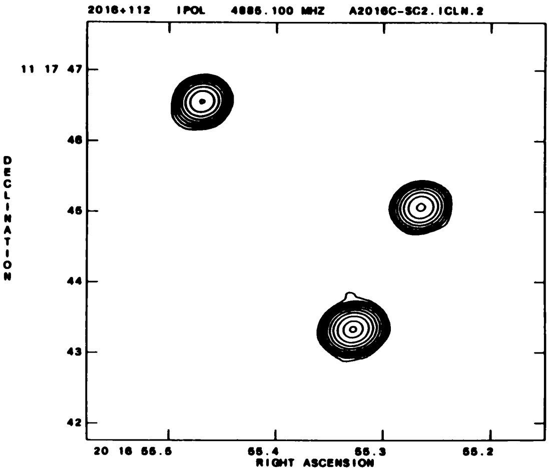

Figure 2. VLA λ6 cm map of 2016+112. December 1984 data: A upper left, B upper right, C lower; contours .25, .5, 1, 2, 4, 8, 16, 32, 64, 95% of peak flux 50 Jy.

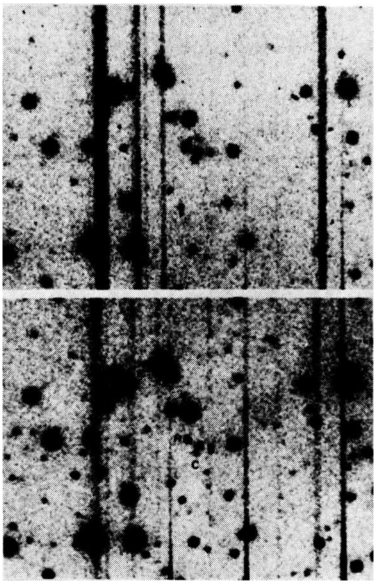

Figure 3. 2016+112 at redshifted Lα (upper) and g-band (lower); taken with PFUEI and Palomar 5m telescope.

upper frame was taken through a narrow filter that passes the redshifted Lα line at λ5180 Å, and the lower is an image through a g filter. The relatively bright appearance of C in the Lα filter shows the influence of the third quasar image, while the two emission patches in the upper picture are absent in the lower frame.

The lensing properties of the single galaxy D [whose corrected absolute magnitude $M_B = -22.5 \pm .2$ ($H_o = 60$, $q_o = 0.5$) makes it a typical bright cluster galaxy] are not well adapted to explaining the observations, as Narasimha , Subramanian, and Chitre (1984) have pointed out. There is no evidence for an associated cluster in the deep optical photographs that have been taken; if a cluster is present, all of the members except C and D are fainter than r = 26.

5.3 0023+171

This, the second lens example to be found from the examination of MG sources described above, is a multiple radio source, as shown in Figure 4. The optical field shows a faint ($r = 23^m$) pair of stellar images, one source being closely coincident with the unresolved radio source to the NW, and the second falling close to the skewed tongue near the center of the double-lobed radio object. No galaxies are visible. The identification by Hewitt *et al* (in preparation) should be described as "probable" in view of the preliminary state of the data, but the indications are convincing that this is another example of a gravitational lens.

The spectra of the visible images are shown in Figure 5. Two lines are evident in both spectra, a strong line at λ7253 and a weaker line at λ7530. These correspond to OII λ3727 and NeIII λ3868 at a redshift of 0.946. The principal difference in the spectra is in the underlying continuum; the object with the fainter lines has the stronger continuum. This may be caused by the presence of a faint galaxy, closely coincident with the quasar, although there is no extended luminosity visible. The absence of visible galaxies in the field implies that once again one has a lens composed of dark matter. The lens redshift is most probably around 0.3, and a giant cD galaxy at that redshift would surely be visible in the deep CCD images taken of the object.

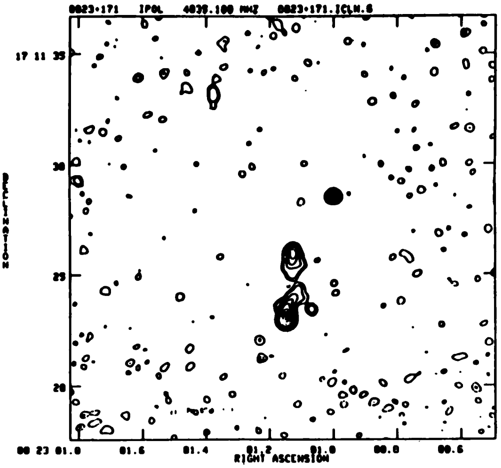

Figure 4. VLA λ6 cm Map of 0023+171 contours 0.5, 1, 2 4, 8, 16, 32, 64, 95% of peak flux 28 mJy.

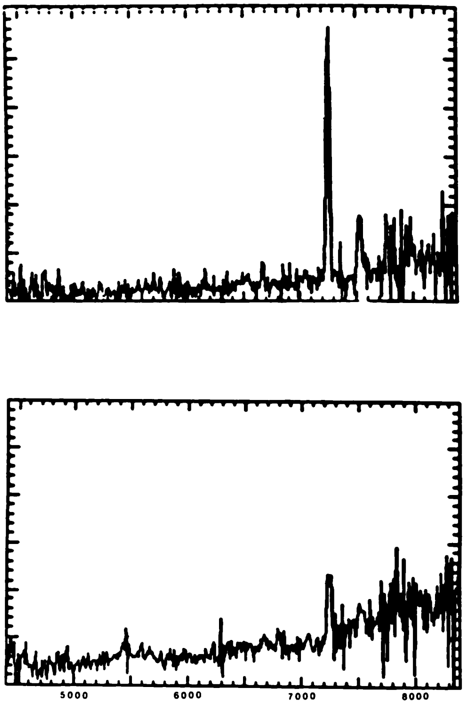

Figure 5. 4-Shooter spectra of 0023+171; A (upper) and B (lower).

6. SUMMARY

The evidence is now at hand to show that the lensing phenomenon is common enough to be a reasonable subject of study and not just a curiosity. The phenomenon is not so common, however, that it forces major reconsideration of the quasar luminosity function. The apparent lack of close multiples, with spacings of the order of half to one arc-second, may be an observational selection effect, but if there are not at least one or two per thousand quasars, there will be a genuine cause for concern. The number of large-separation pairs is in itself surprising, and provides evidence for the widespread distribution of non-luminous matter in the universe. A striking, and not unrelated phenomenon is the anomalous character of at least six of the seven known images. In the case of 0957+561, rational models can be constructed that fit the data, but it looks like a lucky accident in which the caustic between the one- and three-image loci barely includes the quasar in the multiple-image regime. The sources 0023+171, 1653+267, and 2345+007 all seem to be deficient in foreground material that might form a lens, while 1115+080 and 2016+112 do not have foreground galaxies in the proper place to act as the desired lens. The evidence is building for a large-scale dark component in the universe, not necessarily the same as the dark component inferred to exist in clusters of galaxies.

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REFERENCES

Alcock, C: 1985, Ap. J. 291 L29.
Bennett, C.L. et al: 1986, Ap. J. Supp., in press;
see also Lawrence, C.R., ibid.
Bonometti, R.J.: 1985, Ph.D. Thesis, Mass. Institute of Technology.
Bourassa, R.R. and Kantowski, R.: 1975, Ap. J. 195 13.
Cohen, N.L.: 1985, Ph.D. Thesis, Cornell University.
Djorgowski, S. and Spinrad, H.: 1984, Ap. J. 282 L1.
Eddington, A.S.: 1923, Space, Time, and Gravitation 134 (Cambridge).
Einstein, A.: 1936, Science 84 506.
Falco, E.E., Gorenstein, M.V., and Shapiro, I.I.: 1985, Ap. J. 289 L1.
Florentin-Nielsen, R.: 1984, Astron. Astroph. 138 L19.
Gorenstein, M.V. et al: 1983, Science 219 54; 1984, Ap. J. 287 538.
Greenfield, P.E., Roberts, D.H., and Burke, B.F.: 1979, Science 208 495.
Greenfield, P.E., Roberts, D.H., and Burke, B.F.: 1985, Ap. J. 293 370.
Hege, E.K. et al: 1981, Ap. J. 248 L1.
Higgs, W.J.: 1984, M.Sc. Thesis, University of Manchester.
Huchra, J. et al: 1985, Astron. J. 90 691.
Lawrence, C.R. et al: 1984a, Science 223 46.
Lawrence, C.R. et al: 1984b: Ap. J. 278 L95.
Peacock, J.: 1983, 24th Liege Coll. Quasars and Gravitational Lenses 86.
Pooley, G.G. et al: 1979, Nature 280 461.
Porcas, R.W. et al: 1981, Nature 289 758.
Roberts, D.H. et al: 1985, Ap. J. 293 356.
Schneider, D.P. et al: 1985, Ap. J. 294 66.
Stockton, A.: 1980, Ap. J. 242 L141.
Turner, E.L., Ostriker, J.P., and Gott, R.J.: 1984, Ap. J. 284 1.
Walsh, D., Carswell, R.F., and Weymann, R.J.: 1979, Nature 279 381.
Weedman, D.W. et al: 1982, Ap. J. 255 L5.
Weymann, R.J. et al: 1980, Nature 285 641.
Young, P. et al: 1980, Ap. J. 241 507; 1981a,b, Ap. J. 244 723; 736.
Zwicky, F.: 1937, Phys. Rev. 51 290.

DISCUSSION

Peacock : It looks like 0023+171 is being lensed by a double radio galaxy. First, is not this rather unlikely a priori ? Second, if the quasar is at $z \simeq 1$, you should easily detect the galaxy (unless it isn't at the lower redshift!).

Burke : It is not likely a priori but our selection by using a radio survey would favour radio galaxies being found in the field. In the case of 0023+171 the galaxy is not optically evident, but it might be hiding near the southern quasar.

Rees : I would like to ask about an object which is not claimed to be an instance of lensing, namely the OVV object AO 0235+164. This has a galaxy along the line of sight (within 2 arc seconds). There is no evidence for multiple imaging, and also there is a lot of VLBI data, and evidence of variable 21 cm absorption line profiles. It would be interesting if one could test whether or not this object is displaying magnification. If it definitely isn't, it becomes an object with exceedingly high luminosity, and a prime candidate for optical beaming.

Burke : This OVV was in the list of objects examined by Roberts et.al. with negative results and you are indeed correct in saying that it is important. It should be examined more closely.