GRAVITATIONAL LENSES AND DARK MATTER: OBSERVATIONS

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ABSTRACT. Following a few general comments on gravitational lenses from an observer's perspective, the currently available observations of the six known gravitational lenses are summarized. Attention is then called to some regularities and peculiarities of the properties of the known lenses and to how they might be interpreted. The most important conclusions relevant to the dark matter problem which can be obtained from the current observations are that the distributions of mass and light appear to be quite different in at least some of the lensing objects and that objects with projected M/R values about ten times larger than those ordinarily associated with galaxies exist and are not too rare (assuming $\Lambda = 0$).

1. INTRODUCTION

Before reviewing the currently available observations of the six known gravitational lenses, I would like to make a few general remarks about the advantages and disadvantages of lenses as tools for studying cosmology and dark matter from an observer's perspective.

First, gravitational lenses are typically technically difficult objects to locate and study. They are quite rare with only 5 found among the roughly 3000 known quasars to date and only 1 found by studying individual galaxies. They are usually fairly faint; the quasar images in the known lenses vary from about 16th to about 23rd magnitude. Their angular sizes are small (1/2 to 7 arc sec) and strain the resolution of ground based observations (except for VLB). The time scales over which they need to be monitored are unpleasantly long (weeks to decades). None of these problems are insuperable, particularly given the power of present and planned facilities such as 4m class telescopes equipped with CCD's, the VLA, ST, the VLBA, the NNTT, etc. Nevertheless, it is clear that the potential of lenses (described in the preceding paper by J. R. Gott) cannot be realized by small programs or using modest facilities.

Second and probably more serious, it is not clear whether the elegant but idealized lens experiments devised by theorists can

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actually be carried out in the "dirty laboratory" provided to us by the real Universe. The complexities of the lensing mass distributions and the competition of various lensing and cosmological effects and quasar properties will undoubtedly result in many complications. The situation may well prove analogous to that for the "standard candle" Hubble diagram q_o test, namely elegant and beautifully simple in principle but elusive and beset by systematic uncertainties in practice. Nevertheless, I do not believe we should become discouraged at this early stage of lens studies. We have no tools for studying cosmology against which similar objections cannot be raised. At least lenses offer us a new tool to attack problems against which we have worn the old ones dull. Moreover, lenses have the encouraging property that they can be cosmologically informative on an individual basis, not just in statistical samples. Thus, if we are lucky, we may find the gravitational lens counterpart of the binary pulsar and learn a great deal from the careful study of a single special object. This is a nearly unique possibility for cosmologists. Some of us have taken to referring to such putative, specially useful lens systems as "Rosetta Stone" lenses.

Leaving these larger issues for the future to resolve, I turn now to a review of what is currently (June 1985) known about the six lenses so far discovered and what conclusions or hints may be drawn from their properties.

2. OBSERVED PROPERTIES OF THE SIX KNOWN GRAVITATIONAL LENSES

Given the constraints on the length of this review, it is obviously impossible to consider each of the six known lenses individually in any detail. Thus, Figure 1 and Table I are intended to summarize the available information on 0957+561, 1115+080, 1635+267, 2016+112, 2237+031, and 2345+007.

Figure 1 displays a representation of the optical image of each system, all to the same scale. The quasar images are shown as filled circles while the positions of foreground galaxies, which must participate in and may be responsible for the lensing effect, are indicated by open circles. These plots are based on the best available optical images of each of the lens systems listed above (1 - 6, respectively). The most striking properties of these images are the absence of the third (fifth in 1115+080) quasar image required by the transparent lens theorem in all cases, the general lack of co-linearity between the images and the putative lensing object expected for spherically symmetric lenses, and the unexpectedly large (7) angular splittings of the images.

Table I gives the name, discovery reference, and discovery date for each lens system; the number of lens images detected; the status of attempts to detect the lensing object; the redshift of the lensed quasar; the redshift of the lensing galaxy, shown in parentheses if it is merely a photometric estimate; the maximum angular separation of the lensed images; the brightness ratio of the two brightest images; a brief statement of the evidence that the object is a lens system; the

TABLE I Lens Parameters and Status

Name Ref Date	No. of Images	Lensing Object	z_Q	z_L	$\Delta\theta_{MAX}$	R_{AB}	Lens Evidence	Model	Comments
0957+561 (8) 1979	2 of 3+	Yes	1.41	0.39	6"	1.4	spectra. radio. time delay?	Yes	brightest cluster galaxy
1115+080 (9) 1980	4 of 5+	Yes?	1.72	(0.3)	2"	<1.2	spectra. close bright pair.	No	lens outside image circle ?
1635+267 (10) 1983	2 of 3+	No	1.96	-	4"	4.4	spectra.	No	large $\Delta\theta$ and no lens
2016+112 (11) 1983	2 of 3+	Yes	3.27	(0.8)	3"	1.1 to 1.6	spectra. radio.	No	very faint third image
2237+031 (12) 1984	2 of 3+	Yes	1.70	0.04	2"	1.1	coincidence with galaxy.	No	very small z_L
2345+007 (13) 1981	2 of 3+	Yes?	2.15	(1.5)	7"	3.7	spectra.	No	large $\Delta\theta$ and very weak lens?

status of attempts to make a detailed model of the lensing process; and comments on any unusual or surprising properties of the system. Perhaps the most noteworthy features of this table are the general lack of success in attempts to construct detailed lensing models and the fact that all of the known lenses appear to be unusual or surprising in one way or another.

The presentation of the available data in summary form as given above obscures the fact that there is an enormous variation in how much effort has been devoted to studying the various lens systems. Only 0957+561 has been studied exhaustively so far, and some of the systems could be looked at far more closely than they have to date.

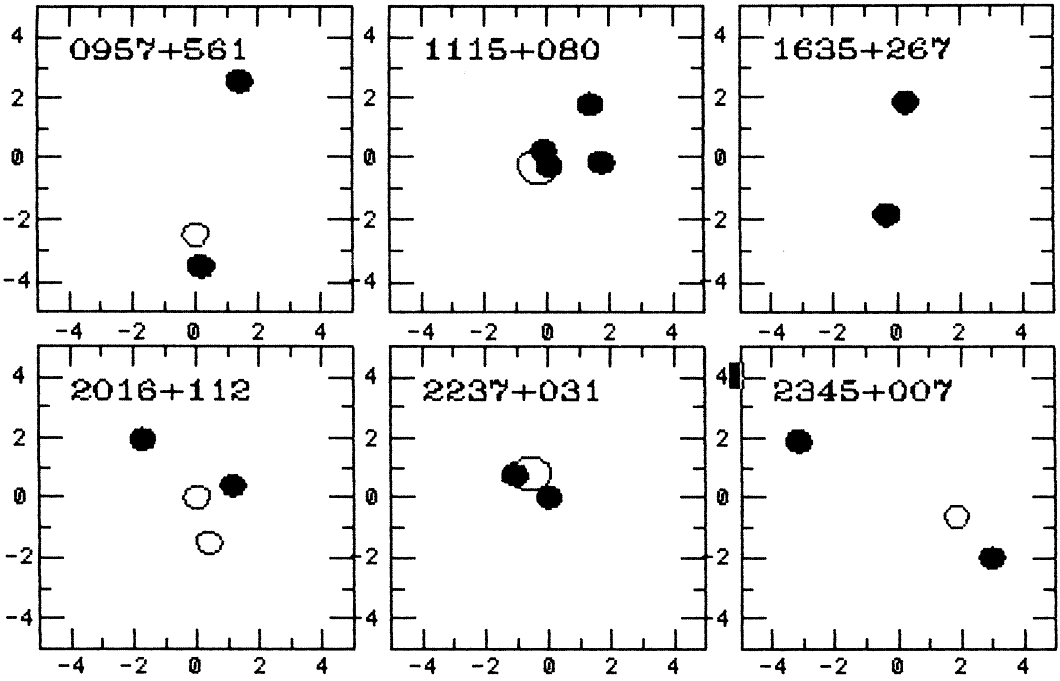

Figure 1. Optical images of the six known gravitational lens systems. Filled circles indicate quasar images, and open circles, probable lensing objects. Each box is 10" on a side.

3. IMPLICATIONS OF THE OBSERVATIONS

Although the six known gravitational lenses do not constitute a statistically valid sample in any sense and probably do not include an example of a "Rosetta Stone" lens, some physically interesting quantities may be calculated from their observed properties and some intriguing hints may be discerned. Several of these are described briefly below.

3.1 Lens Masses

Table II gives the mass of a point mass and the one dimensional velocity dispersion of an isothermal sphere required to produce the observed maximum image angular separation for each of the six known lenses. It also gives the physical radius of the circle just enclosing the two most widely separated images, an upper limit on the radius of the mass producing the splitting via Ricci focusing. These numbers are based on the lens redshifts given in Table I and are thus affected by their substantial uncertainties. A lens redshift of 0.5 has been assumed for 1635+267, and values have been calculated with that lens redshift as well as 1.5 for 2345+007 since it is unclear that the recently discovered (6) and apparently large redshift galaxy in that system is the primary lensing object.

TABLE II Lens Masses and Sizes

Name	$M_p/10^{11}M_\odot$	σ (k/s)	r (kpc)
0957+561	13	427	9.5
1115+080	1.4	241	3.2
1635+267	20	505	8.1
2016+112	7.8	342	7.0
2237+031	0.054	154	0.3
2345+007(1.5)	120	878	14.9
2345+007(0.5)	21	459	12.4

Ho = 100 k/s/Mpc, q_o = 1/2

It should be emphasized of course that these numbers are not based on real models of each lens system and do not attempt to account for any of their observed properties beyond the maximum image separation. These numbers also neglect the effects of shearing due to mass outside the image circle which clearly plays a role in 0957+561 and quite possibly other systems; of course, the mass required to account for the separations by such shearing effects grows very rapidly with the projected distance from the image circle. All things considered, the tabulated numbers probably give a reasonably reliable rough estimate of the projected masses involved in producing the observed lens systems. Their surprisingly large magnitude is of course the same surprise as that associated with the unexpectedly large (7) splittings.

3.2 Mass Distributions vs. Light Distributions

Well observed gravitational lenses offer the opportunity to directly check the classical but now out of favor hypothesis that the mass content of the Universe is traced by the distribution of stars. This is possible because the properties of a lens depend only upon the projected mass distribution in the plane of the sky which is equivalent to the observed lens surface brightness distribution if the hypothesis were correct. The only free parameter left to reproduce the positions and brightness ratios of the observed images is the unperturbed position of the background quasar.

Such calculations have been carried out for 0957+561 (14), 1115+080 (15), and 2016+112 (16). In no case does the observed light distribution account for the observed image properties. In fact no mass distribution in which the mass concentrations are even concentric with the observed light concentrations (i.e., galaxies) has been found to satisfactorily account for the data. The problems are accounting for the dog leg in the image-lens-image line in 0957+561, explaining the asymmetry of the four images with respect to the lens in 1115+080, and reproducing the acute image-lens-image angle and the very faint third image in 2016+112.

This negative result is probably the most important contribution of lens studies to our knowledge of the properties of dark matter to date. It strongly reinforces some earlier clues (17) that the distribution of the dark matter may be extremely poorly correlated with that of stars. If it is confirmed as a general property of lens systems, particularly when based on ST observations which will give us far more reliable and complete determinations of the lens surface brightness distributions, it will amount to a major discovery in my view.

3.3 Dark Objects

One possible exciting gravitational lens discovery would be a system in which the combination of the angular splitting of the images, the redshift of the lensed object, and very deep negative searches for the lensing object effectively ruled out the possibility of lensing by any known type of astronomical object and thus required the existence of a massive dark object. In such a system it would be possible to place a lower limit on the M/L of the lensing object and thus to detect in effect a dark object. Such a conclusion would have to contend with the possibility that the particular system was actually not a gravitational lens at all and the possible alternative explanation that $\Lambda \neq 0$, which allows less massive and higher redshift objects to produce larger splittings.

None of the known six lens systems are unambiguous examples of this situation, but two of them, 1635+267 and 2345+007, are promising.

Very deep CCD images of the former reveal no candidate lensing object (18) while only a very faint and apparently distant object which is probably incapable of producing more than a small fraction of the observed 7" split has been found for the latter (6). The existing data probably rule out all but the most extreme sorts of known astronomical objects as the lenses in these systems; even these possibilities could be ruled out by deep ST images.

3.4 Number of Images

A quite rigorous mathematical theorem (19) requires that all transparent gravitational lenses produce an odd number of images. The observations of the six known lens systems are unanimous in revealing an even number of images (two in all but one case) in each system. It is not clear whether this clear disagreement of theory and observation is an important hint of some sort, a fluke, or merely a misleading reflection of some bias or shortcoming of the observations.

The most straightforward explanation for the discrepancy is the possibility that the lenses are not transparent; at optical wavelengths dust could be the culprit, but in the radio (only relevant for 0957+561 and 2016+112) there is no such natural possibility. The other obvious possibility is that the n+1 th images are generally much fainter than the first n images. In cases with spherical symmetry, this can be arranged by assuming very cuspy or even singular (i.e., a black hole) central density distributions.

Of the known lenses, this problem is probably most serious for 2016+112, a system for which high quality VLA maps rule out a third image as bright as 0.1% of the observed images over most of the field (20).

3.5 Distribution of Image Angular Separations

The definitive comparison of observations of the distribution of image angular separations to theoretical predictions (21) will have to await better controlled and understood statistical samples of lenses; however, if the current predominance of 5 ± 2 arc second splittings and the absence of <1" cases is not reversed by such samples, it will present a major puzzle (or clue?) concerning the nature of the lensing masses. Possible explanations include a remarkably close coincidence of the surface densities of large structures in the Universe with the critical lensing surface density, and $\Lambda \neq 0$. It would be particularly hard to understand the absence of a substantial number of <1" separation systems since these should be produced by the inner regions of ordinary galaxies whose mass distributions are thought to be well known from rotation curve studies (22). Of course, this dilemma is not yet upon us since it is based on a rather uncertain extrapolation of the current observational situation.

3.6 Brightness Ratios

It is interesting to note the rather bimodal distribution of observed brightness ratios (of the two brightest images) in Table I in which four of the systems have $R_{AB} < 1.5$ while the other two have $R_{AB} \approx 4$. It is also curious that the two systems with large brightness ratios are 1635+267 and 2345+007, the same two which are possible candidates for being lensed by dark objects (23). The distribution of brightness ratios can be used as a diagnostic of the mass distribution in the lensing objects in principle (24). Could this be another indication that the lensing object in these systems is of an unusual nature?

3.7 Lensing By Low Mass Objects

No unambiguous, or even very suggestive, evidence for lensing by low mass objects (minilensing) has been reported to date. Of the known lenses, 0957+561 and 2237+031 appear to be particularly good candidates for minilens searches (25). The absence of a third image in any particular system could be blamed on a minilens event, but this would not be a satisfactory statistical explanation since such events can also brighten images.

4. SUMMARY AND DISCUSSION

The observations of gravitational lenses to date lead to two fairly definite conclusions relevant to the dark matter problem. First, it is clear that the distribution of mass in the Universe is not the same as the distribution of light (i.e., stars); moreover, in some systems the center of mass is not even coincident with the center of light. Second, projected mass distributions with $M/R > 10^{12}\ M_{\odot}/10$ kpc exist and are not too rare (or perhaps $\Lambda \neq 0$).

In addition, the existing lens observations hint at two further conclusions without establishing them with any certainty. First, the possibility that some of the lensing objects may be dark (very high M/L compared to ordinary astronomical systems) must be taken seriously. Second, there is some indication that the lensing objects have very compact, or even singular, cores.

To date, the observations have not provided us with examples of small angular separation (<1") lenses, minilensing events, or simple "Rosetta Stone" lenses. Observers must continue to seek for examples of these intriguing possible systems.

Four general types of observations are needed to advance gravitational lens studies: lens surveys designed to produce statistically useful samples and to reveal "Rosetta Stone" lenses, detailed studies of known lens systems (not just 0957+561), flux monitoring programs designed to detect minilens events and determine time delays, and measurements of distortions in resolved background objects produced by the lensing effect of foreground galaxies. Some effort is being made in each of these areas. J. N. Hewitt describes a major VLA -optical lens survey, and A. Tyson describes observations of the fourth type listed above elsewhere in this volume.

Given that the first known gravitational lens was discovered only six years ago, it seems to me quite reasonable to hope that they yet have much to tell us about dark matter and other cosmological issues.

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ADDENDUM

The editors have generously allowed me to update the summary of the gravitational lens observational situation described in the preceding paper (current for June 1985) as the proceedings go to press (currently late December 1985). There have been several important developments and changes:

A new probable gravitational lens 0023 + 171 (Hewitt et al. 1986) has been discovered. Two images but no lensing object are seen. The source redshift is 0.95 and the angular splitting of the images is 5". Both components are radio sources and one shows radio jets/lobes. The optical line brightness ratio between the two components is about 3 to 1.

The lensing galaxy in 1115 + 080 reported by Henry is, after further image analysis, said to be located essentially directly in between the A and A' images (Henry and Heasley 1986). In addition, Shaklan and Hege (1986) dispute the existence of the galaxy reported by Henry and Heasley and instead report a galaxy in a different position. The small angular size of the 1115 + 080 system and the bright apparent magnitude of the A - A' component make detection of a lensing galaxy particularly difficult for this system.

Schneider et al. (1986) report new observations of 2016 + 112 which reveal the third image located very near the center of the lensing galaxy C, the redshift of the lensing galaxy D (1.01), and the existence of two slightly resolved emission line regions to the northwest and west of components A and B, respectively.

Further image analysis by Tyson of his 2345 + 007 data indicate that the tentative detection of a very faint lensing galaxy in that system was spurious. It is now reported that any lensing galaxy between the two images must be fainter than J = 25.5 (Tyson 1986).

All references in this addendum are to preprints.

DISCUSSION

WHITMORE: It seems possible that a slightly asymmetric massive halo may have its center of mass displaced from the center of light. This could explain the discrepancy you report. Can you tell us how great the displacement might be?

E. TURNER: The results are fairly model dependent, but 20 kpc might be a typical value.

BALBUS: What is the timescale for twinkling due to minilensing in the Huchra lens?

PACZYNSKI: If the minilenses are stars of 0.5 - 1 $M_{\odot}$, the timescale is something like two years.

MADSEN: Are diffraction effects negligible for minilensing?

GOTT: You are observing a distant object with a telescope that's a minilens with a projected size of $\sim 10^{-6}$ arcsec. Diffraction becomes important if you look at radio wavelengths longer than about 60 cm.

REES: Some of the things you said about M/L in the lens assume there is no minilensing, don't they? Your evidence wouldn't be the same if you took minilensing into account.

E. TURNER: You could use minilensing to explain our inability to get the brightness ratios right. But you have the additional problem of not having the right number of images in the right places. All of the models fail for that reason. You can't get out of that with minilensing, except to the extent that you could temporarily erase one of the images.

OSTRIKER: On the question of the absence of the central image: Isothermal-sphere models certainly predict that there will be one, but has anyone looked at what happens if you model galaxies using de Vaucouleurs laws, which have singular centers? Are they singular enough to prevent the formation of a central image?

GOTT: When you use a singular isothermal sphere, then as the core radius shrinks to zero, the little core images shrink to zero intensity. That is singular in the sense that we want. For example, our Galaxy has a singular enough core to knock out the central image.

OSTRIKER: But I'm asking in particular about the de Vaucouleurs model, which is not as singular as the isothermal sphere.

PHINNEY: The answer is no, because the model has a finite central surface density. All that matters is the projected surface density.

E. TURNER: In any particular system you can always make the third image faint by making the core radius small. But as long as it is finite, there will be configurations where the central image will be fairly bright. For example, in 2016+112 I think a de Vaucouleurs law is not centrally concentrated enough to eliminate the central image.

BURKE: Bonometti, Shapiro et al. have shown that for 0957+561 the compact VLBI source which had been suspected as the third image is in fact not the third image. It may be the core of the giant galaxy G1.

WHITE: Can the absence of a third image plausibly be ascribed to obscuration in the lens in any of the known systems?

E. TURNER: Yes, this may be important for 1115+080, 2345+007, 1635+267, and 2237+031. It cannot be the problem for 0957+561 and 2016+112, which are radio sources with excellent VLA images.

PACZYNSKI (to GOTT): I think that your limit $q_0 > -2.3$ is not quite as stringent as you say, because if the opposite side of the Universe is not exactly at the redshift of the source, but between us and the source, then the argument you presented doesn't work.

GOTT: If the object you were looking at were just beyond the antipodal point, it would not in general produce a double lens image. A QSO just beyond the antipodal redshift could be double lensed only by a very low-redshift galaxy, and the optical depth for this is small. Another thing that happens is that, as you approach the antipodal point from this side, all the lens cross-sections blow up, because the Universe is acting like a big magnifying glass. If this happened, say, at a redshift of 3, you would see a tremendous number of large-separation double quasars at redshift 3. Just beyond that there would be a wall: you would see no quasars. So the optical depth is not a linear function of distance. A third effect is that we would see a big dependence of the lens splitting on z. We don't see that; the splittings are more-or-less constant, as you would expect in a Friedmann model.

TYSON: Regarding the apparent paradox if 2345+007 is lensed by a single M_* galaxy at $z \approx 1.5$: There is evidence for at least one foreground cluster.

E. TURNER: Yes, it would be much easier to understand 2345+007 if the dominant contribution to the total bending angle were at a $z < 1$.

CARR: It is worth stressing that VLBI observations already limit the number of lenses much smaller than galaxies. Of a sample of 50 sources, 5 show double structure on the milliarcsec scale with the components having comparable spectra. Even if this double structure does not result from lensing, one can infer that dark objects in the mass range around 10^6 $M_\odot$ cannot have more than a tenth of the critical density.

E. TURNER: Yes. Given the absence of a statistically well defined sample of lenses, the strongest statistical results are presently based on the absence of the lenses predicted by some models of dark matter.

BURKE: The range of separations from 1" down to $0\overset{''}{.}1$ or maybe $0\overset{''}{.}01$ has been investigated little or not at all. Some efforts are now under way to remedy this lack.

E. TURNER: The VLA survey, which should cover $\Delta\theta > 0\overset{''}{.}3$, is briefly described in a poster paper by J. Hewitt, et al.

SHAPIRO: What range can we assume for the observational coverage of angular splittings for lensed images? Can we, for example, assume that all 1' splittings are known? Would we identify lensed images if their splitting were even larger than 1' , say 1°? How about splittings which are smaller than 2"?

E. TURNER: The current situation is very complex; clearly some QSO's have been examined very carefully and others hardly at all. My rough guess is that for splittings between several arcseconds and about 1 arcminute and for small to moderate brightness ratios we have not missed many lenses among the known quasars.

SCHECHTER: Can you tell us a bit about VV172? Is it an interesting lens system?

E. TURNER: Yes, it is interesting. Tod Lauer has taken a picture of the chain and subtracted all the nearby galaxies to show the shape of the background galaxy. You can then put enough mass into the group to bind it, and ask what the intrinsic shape of the background galaxy must be so that it looks the way it does after lensing. The result is slightly banana-shaped. There is considerable freedom in these models, which are by Hyung-Mok Lee and Gott. In principle, though, you could use systems like this to put constraints on how the mass is distributed by saying what you are willing to believe about the undistorted image of the background object.

PACZYNSKI: In this model, what is the amplification factor? Does the luminosity of the background galaxy agree with its observed color?

E. TURNER: The amplification is not very large, about a factor of two. That helps, but does not entirely account for the color-luminosity discrepancy. It's hard to produce enough amplification to explain the color discrepancy without producing an unreasonable distortion which then has to be exactly cancelled by some unreasonable shape.

PACZYNSKI: You get the distortion if you assume that mass is distributed like light. You suggested that this is not the case in the known lenses.

E. TURNER: Yes. A smooth mass distribution gives magnification without disortion.

WHITE: Has the velocity dispersion of the background galaxy in VV172 been measured to see if it is what you'd infer for the color and distance you adopt?

E. TURNER: No, but that's a good idea which had crossed my mind.