Gravitational Lenses: Observational Status

INTRODUCTION

There are now four well verified examples of the gravitational lens phenomenon, in which the light from a single distant object is scattered into several images by the gravitational field of an intervening mass. In this Comment the current status of our knowledge of these objects will be summarized and placed in an astrophysical context. The first example, the double quasar 0957+561, was discovered by Walsh *et al.*[1] in 1979 as a result of their program to make optical identifications of a list of radio sources whose positions had been accurately measured by Porcas *et al.*[2] The second case, the triple quasar 1115+080, was discovered by Weymann *et al.*[3] in the course of taking spectra of quasars contained in the Green and Schmidt catalog of bright quasars. Weedman[4] found that one of the objects, the double quasar 2345+0007 in his Schmidt-Objective prism search, was another instance of lensing. The fourth case, the triple source 2016+112, has just recently been discovered as the result of a collaboration between groups working at the VLA and at Mt. Palomar (Lawrence *et al.*, in press). The first and fourth are detected at radio and optical frequencies, while the second and third appear to be undetectable at radio frequencies.

The fundamental criterion that must be met for an object to be considered as a gravitational lens stems from Einstein's principle of equivalence: All photons must have the same trajectories in a gravitational field. This means that a distant quasar gravitationally lensed

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by an intervening mass must exhibit the same spectra in all images from radio frequencies, through the infrared, optical and ultraviolet range, and into the detectable x-ray domain of the electromagnetic spectrum. If there are anomalies, the burden of proof is upon the observer to give a satisfactory explanation. All four lens examples satisfy this requirement; it will be seen that apparent discrepancies can be of vital interest.

BASIC PHYSICS

Einstein was fully aware that gravitational lensing could occur, although improbable for stars. Zwicky[5] seems to have been the first to advocate searching for examples in an extragalactic context, followed by Refsdal[6] who gives a literature survey as it stood in 1964. Press and Gunn[7] had proposed looking for massive black holes in intergalactic space by studying the distortion of background galaxies, and concluded that black holes of 10^{12} $M_\odot$ were not common. The realistic case of an ellipsoidal galaxy lensing a quasar was solved in detail by Bourassa and Kantowski.[8] Curiously, Krolik and Kwan[9] revived the subject just as the discovery by Walsh *et al.* was being made.

The basic calculations are easily described. Photons travel through space subject to the transverse accelerations of the gravitational forces of matter in the universe. The simplest case, deflection by a point mass M, gives a good illustration of the effect. The Newtonian calculation has to be amended by Einstein's General Theory, which requires a correction by a factor of 2; the result for the point-mass case gives an angle of deflection θ; in terms of the Schwarzchild radius $R_s = 2\ \mathrm{GM}/c^2$ and the impact parameter,

$$\theta = 2R_s/b\,. \tag{1}$$

The geometry is shown in Figure 1, which shows a quasar at distance D, a point mass at distance D_m, and an undeflected angle β between M and O that would have been seen by an observer at O. Because of the deflection the actual angle measured is α. For the point mass, the photon actually travels in a hyperbolic orbit and two solutions

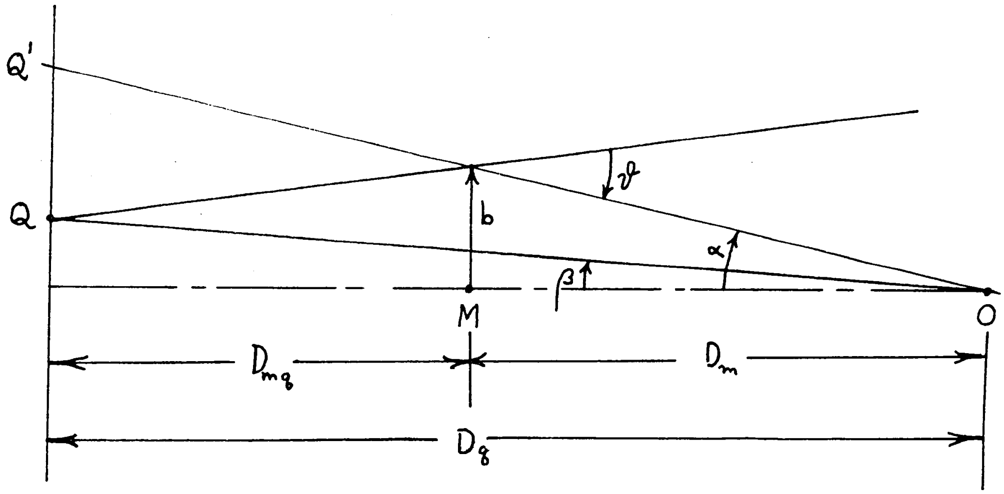

FIGURE 1 Geometry of gravitational lens.

exist, giving a principal image at α_1 and a secondary image at α_2. These must appear on opposite sides of M as projected on the image plane (x_i, y_i) through M, since OMQ defines a plane and the orbits must be in that plane. The behavior of the images as the position of Q varies is instructive, and is illustrated in Figure 2. The degenerate case of OMQ lying in a straight line (Figure 2a) gives a ring image with the magnification going to infinity as the object size shrinks to a point. (The interposition of the lens does not change brightness,

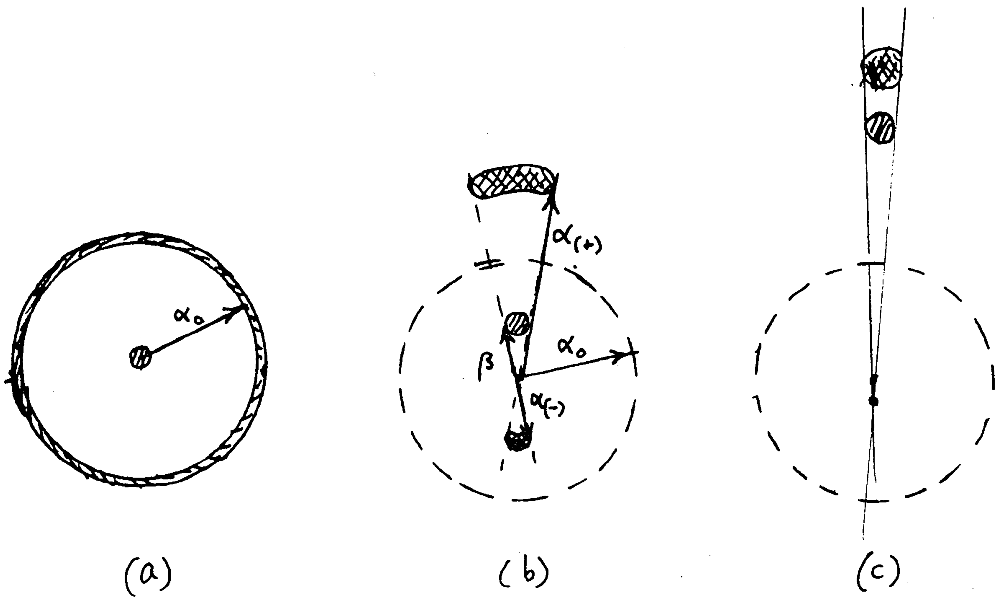

FIGURE 2 Appearance of images: (a) aligned, (b) small β (c) large B.

so magnification is given by the ratio of the solid angles $d\omega_0$ and $d\omega_i$ of the object and image.) The apparent ring radius is

$$\alpha_o = \sqrt{2(R_s/D_m)(D_{mq}/D_q)}\,. \tag{2}$$

This sets the scale of the order of magnitude of gravitational lensing effects. For a point mass of 10^{12} $M_\odot$, half-way to a quasar at 3 Gpc, and neglecting cosmological complications $\alpha_0 \simeq 2$ arc s.

When the source is not aligned with the point mass, there are two images at angle of α_1 and α_2. The angle of deflection (1) must satisfy the geometric condition

$$\theta = (D_q/D_{mq})(\alpha - \beta)\,, \tag{3}$$

and equating this to Eq.(1) (letting θ be a function of $\beta = b/D_m$)

$$\alpha = \beta/2 \pm \sqrt{(\beta/2)^2 + \alpha_o^2}. \tag{4}$$

If β is comparable to α_o, the results are as illustrated in Figure 2b. The principal image moves out beyond the singular circle, and the secondary image moves in. In the 10^{12} $M_\odot$ numerical example quoted, if the misalignment angle $\beta = 1$ arc s the images appear as crescents, the principal image at 2.56 arc s with magnification $M = 1.6$ and the secondary image at 1.44 arc s with magnification $M = -1.1$ (with the negative sign indicating image inversion). As β increases to a larger value, the primary image approaches the undeflected image, while the secondary image shrinks to the origin, rapidly fading to nothing.

Deflection by a general mass distribution at M is conceptually similar. Since the angle of deflection is small, the three-dimensional density ρ can be replaced by a surface density α projected on the image plane if M is compact compared to its distance. The scattering angle θ is a function of impact parameter (or deflection $\alpha = b/D_m$) and if the distribution is spherically symmetric, the solution proceeds in the same fashion, described graphically in Figure 3. The scattering law $\theta(\alpha)$ asymptotically approaches the hyperbola of the point-mass case [Eq.(1)] for large α, and must go to zero for a ray through the center. The geometric condition, Eq.(3), must still be satisfied, and this is just a straight line whose slope is D_q/D_{mq} and whose y intercept goes ever more negative as β increases. The intersection of the two curves defines the image location; primary image(s) to the right, secondary images to the left. The equation to be solved is generally transcendental, but several generalizations are clear. The number of images must be odd, there is a maximum impact parameter beyond which there is only the primary image and no secondary images and if β is just inside this limit, with the line just nicking the scattering curve, the pair of images will appear with high magnification. For a general surface distribution, the solution process is identical except that the quantities are replaced by their vector equivalents $\theta(\alpha)$, α, and β. One should remark, however, that despite this conceptual simplicity it is not easy to anticipate results for complex mass distributions.

THE TWIN QUASAR 0957+561

The two quasar images of magnitudes 17.3 and 17.6 are separated by 6″, and the emission-line redshifts of 1.4 are coincident to within 50 km s^{-1}.[14] The absorption line systems are similar in both images.

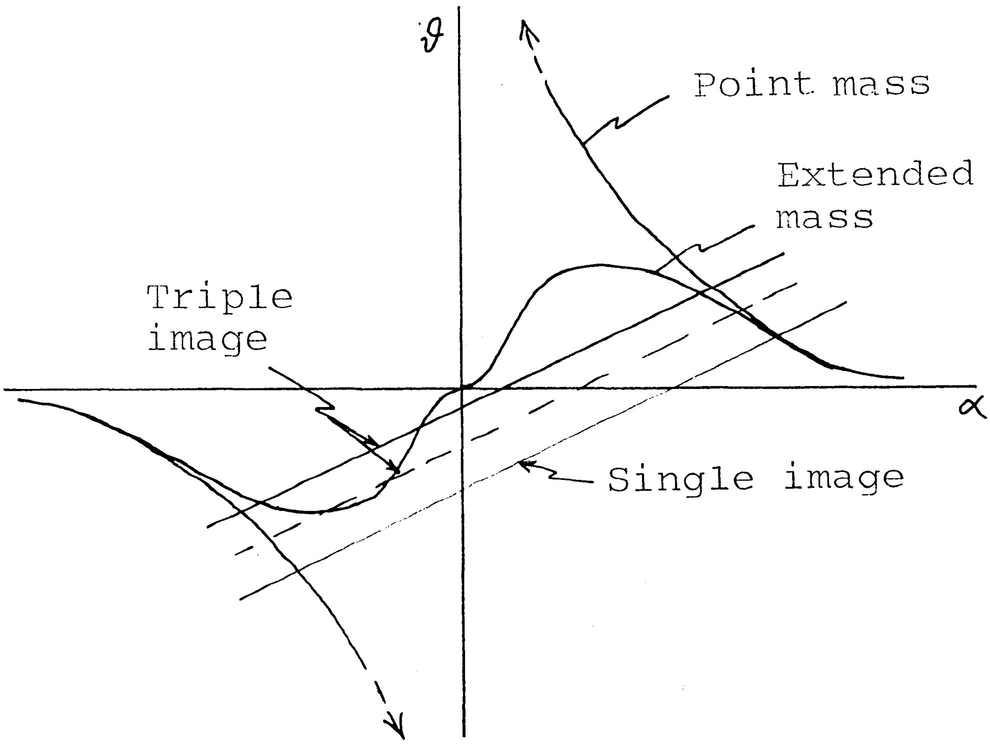

FIGURE 3 General scattering law: image formation conditions.

A recent VLA radio map of Roberts *et al.* (in press) is shown in Figure 4. The quasar locations are at A and B, there are prominent radio jets NE and SW of A with no apparent counterparts at B, and there is a small source G near B. These anomalies, and the presence of an annoying discrepancy between the optical spectra of A and B, raised serious questions until they were cleared at one stroke by the observations of Stockton[10] at Mauna and Young *et al.*[11] at Mt. Palomar. These showed a giant cD galaxy of magnitude $m = 18.5$ centered on G. The spectral difference was caused by the added spectrum of G, whose H-K break yielded a redshift of 0.36. The 200″ observations showed that the galaxy designated G1 was the brightest member of a rich cluster scattered across the entire 200 arc s CCD camera field. Young *et al.*[12] and Greenfield[13] showed that no

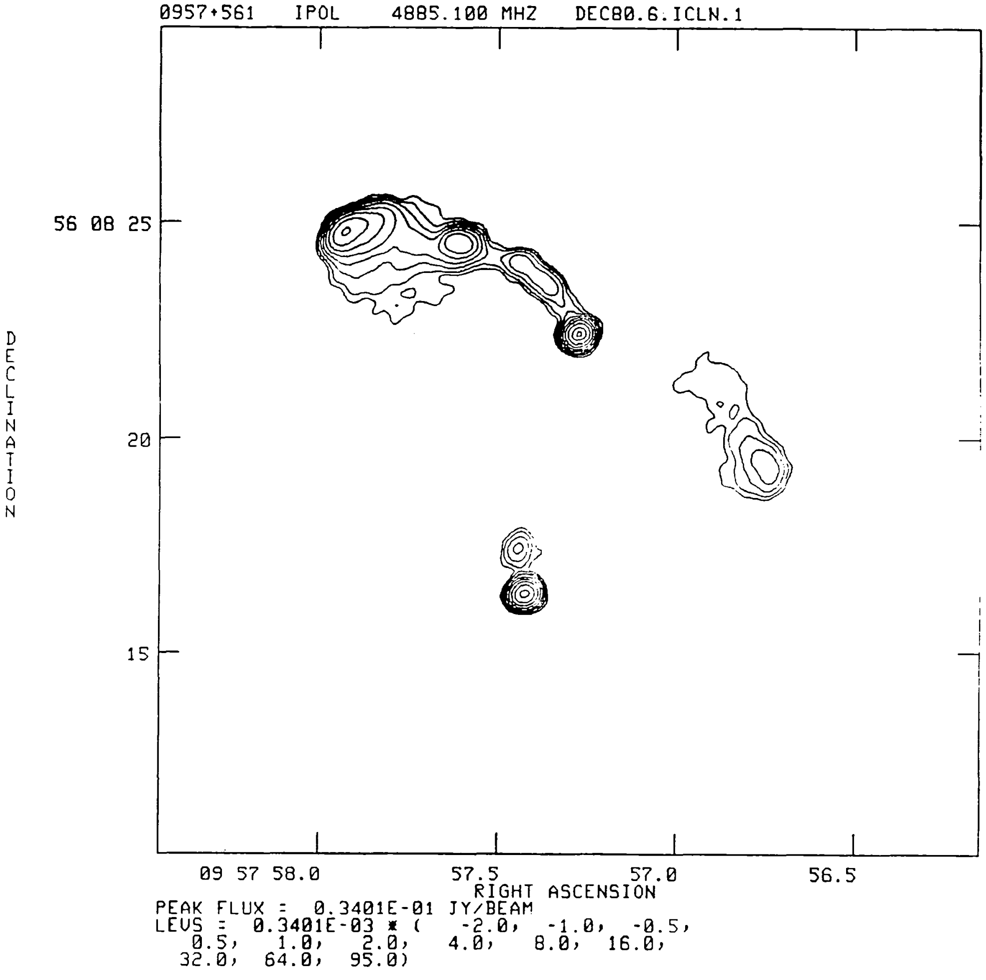

FIGURE 4 The gravitational lens 0957+561 observed at 6 cm with the VLA (Roberts *et al.*).

plausible distribution of matter associated with the visible galaxies could explain the data. Young *et al.* presented a model, generally referred to as the Young double-ellipsoid model, that has far greater promise. One elliposidal matter distribution (a King distribution) is centered on the galaxy, with the ellipticity and position angle fixed by the optical data, the scale length and velocity dispersion being free paramters. The second elliposid represents the approximate distribution of matter associated with the cluster; its position, ellipticity, orientation, scale length and velocity dispersion are freely adjustable.

It would seem that with eight adjustable parameters any set of observations could be fitted. This is not the case: Young commented that "VLBI observations present a new set of contraints." Porcas *et al.*[14] showed that each quasar has core-jet structure, with the jets about 50 mas long and lying at nearly the same position angle. Roberts *et al.* (in press) have shown that the directions of linear polarization are also nearly parallel. Any model, therefore, must satisfy the condition that a vector in the object transform into vectors in the two images that have been rotated by the same amount. Greenfield took all these constraints and showed that the Young double ellipsoid model worked reasonably well; the derived parameters are given in Table I.

The VLBI observations are continuing; Gorenstien *et al.* (in press) have shown that each quasar core in turn has a jet structure of the order of 1 mas.

Where is the third image? It may be the compact source near the center of G1 seen by Gorenstein *et al.*[15]; in any event, it must lie near the core of G1. Investigation is continuing; Roberts *et al.* (in press) may have seen the multiply-imaged portion of the NE jet near B. In any event, it is impossible to escape the conclusion that there is a large amount of nonluminous matter associated with the cluster and not distributed in the same fashion as the member galaxies.

TABLE I
Parameters for the Young double-ellipsoid model

	Galaxy G1	Cluster
Scale length (=3 core radii), kpc	0.44	50
Velocity dispersion, km s^{-1}	200.1	1005.5
Axial ratio	0.8	0.8
Position angle	53°	103°

Cluster center-of-mass with respect to G1 $X_c = -8''.00$ $Y_c = -6''.44$.

THE "TRIPLE" QUASAR 1115+080

Originally, three images of 1115+080 were reported[3] showing identical spectra with redshifts of 1.722. One image is relatively bright, having magnitude m = 16.3; the other two are fainter, at magnitudes m = 18.6 and m = 18.2, separated by $1''.77$ and $2''.28$ at position angles 226° and 322° with respect to the bright image. The object is radio-quiet: Greenfield, Roberts and Burke (unpublished) placed an upper limit of 40 μJy on its 6 cm radio flux. Young *et al.*[16] proposed that a single galaxy is acting as the lens. There should be five images in his model, and Hege *et al.*[17] showed that the bright image appeared to be double, as predicted. Henry (private communication) observed this object at Mauna Kea under $1/3''$ seeing conditions and confirmed the reported splitting, at the same time obtaining what appears to be the image of a foreground galaxy, although its exact placement is not exactly that predicted by Young *et al.*

THE DOUBLE QUASAR 2345+0007

The two quasar images exhibit magnitudes of 20 and 21 with a redshift $z = 2.15$, according to Weedman *et al.* Their separation is $7''.3$, and there is no 6 cm radio flux above 2 mJy (Burke *et al.*, unpublished). No lensing has yet been seen, despite a deep CCD search to magnitude 23 by Keel.[18] The wide separation and lack of a visible galaxy suggest that a distant cluster is acting as the lens. Inspection of Eq.(3) shows that it is increasingly difficult to obtain a separation of $7''$ as D_m approaches D_q without invoking an enormous mass for the lens.

THE TRIPLE SOURCE 2016+112

This recently discovered lens example was identified as one of several lens candidates by Lawrence *et al.* (in press) in an extensive collaboration involving both radio observations (at the VLA) and optical observations with the $200''$ Hale telescope. The radio map, one of a sample of 1000 snapshots taken of sources from the MG Survey (the MIT-Green Bank Survey, in preparation), showed three compact radio sources, forming a right triangle of sides $3''.4$ and with the strongest radio component lying southernmost. All three sources showed optical counterparts. The strongest radio component coincides with a faint diffuse object of $23^m.5$, the weakest optical image of the three. The other two are stellar, and are each of magnitude 22.5. The stellar components show emission-line spectra with lines of Ly-α λ1216, CIV λ1240, H_eII λ1640, and the blend of CIV-OIV λ2400. The redshifts are 3.27 and are equal in recession velocity to within 50 km s^{-1}.

If the diffuse object is a galaxy, it does not appear to be the sole lensing agent unless it is both very massive and very flat. A spherical cD galaxy, even if very massive, would not do unless it were a member of a cluster providing extra lensing mass. There is, of course, the possibility that the fluctuations in density along the line of sight have caused a random walk in the ray paths and have destroyed what would have been a proper pair lying to either side of the galaxy. The observations were taken at the end of the 1983 observing season, and further information will be eagerly awaited in 1984.

COMMENTARY

Each example of a gravitational lens has proven to be a unique puzzle. Ostriker and his colleagues (in preparation) have predicted that ordinary galaxies should act as lenses on background quasars with moderate frequency: They would expect a minimum of two examples per thousand quasars, with six per thousand being a reasonable expectation. The resulting doubles would exhibit separation whose distribution function peaks at 1 arc s or less, and they point out that the present (admittedly poorly sampled) set is quite different from this expectation. When the lensing galaxy lies in a cluster the cluster mass enhances the splitting, and at least two of the present cases are probably of this sort. Thus the lensing phenomenon, if discovered in enough instances, should be a powerful probe for establishing the masses of galaxies and clusters of galaxies, with the hope of defining the distribution (or existence) of dark matter in the universe.

The ray paths of the different images are not the same, and many quasars vary on time scales of days and years. The images should vary, therefore, with time series that are identical but shifted by the relative delay. The effect was noted by Gott and Gunn,[19] calculated by Cooke and Kantowski[20] and its complications have recently been explored by Young, Canizares, and Alcock. In view of the difficulties in obtaining cosmological facts by traditional methods (H_0 probably lies between 30 and 120 km s^{-1} Mpc; the sign of q_0 is not established) one need not be deterred by complications, although at the same time one should not expect the cosmological secrets to be revealed without effort.

Note added in proof: Another example of a gravitationally lensed quasar pair, 1635+267, was tentatively proposed by Weedman *et al.*, but no redshift had been obtained. Verification of identical redshifts for the pair has been announced by S. Djorgowski and H.S. Spinrad (private communication), who find that the images, separated by 4″ with R magnitudes 19.15 and 20.75, have redshifts of 1.961. No candidate for a lensing galaxy is visible. The distinct tendency continues for relatively large separation to occur between lensed image pairs.

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