GRAVITATIONAL LENSES

J. N. HEWITT
Department of Physics and Research Laboratory of Electronics
Massachusetts Institute of Technology
Cambridge, Massachusetts 01239 USA

Abstract. In approximately half the systems currently recognized as strongly gravitationally lensed, the background object is an extragalactic radio source. Radio observations have played an important role in the identification of lensed systems, and the properties of radio sources allow some of the astrophysical applications of lensing to be realized. High redshift galaxies can be studied through lens modeling and by observing more than one ray path through the lens. The morphological, spectral, and polarization information of high resolution radio images provides strong constraints on the mass distribution in the lensing galaxies. On cosmological scales, radio variability has been applied to the time delay measurement of angular diameter distance.

1. Introduction

Since the discovery of the first gravitational lens in 1979, many new cases of multiple imaging by a gravitational lens ("strong lensing") have been discovered. Other manifestations of gravitational lensing have also been observed, such as the distortion of background galaxies ("weak lensing"), microlensing, a possible statistical excess of quasars near foreground galaxies, and the time delay exhibited in the light curves of images of the same object. In this paper, I restrict my attention to just the strong lenses. Table 1 presents a summary of the strong lenses currently known. A recent summary of the data on these objects is given by Keaton and Kochanek (1995). A large number of the strong lenses are radio sources, and in many cases radio data provided the first evidence for gravitational lensing. The radio data have been important in identifying lenses and providing infor-

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TABLE 1. Strong Gravitational Lenses

Object	Number of Images	Lens[1]	Source[1]	z_l	z_s	Radio Source	Ref[2]
0023+171[3,4]	2	G?	G	?	0.95	Yes	H87
0142-100	2	G	Q	0.49	2.72	Faint?	S87
0218+357[4]	2,ring	G	?	0.68	?	Yes	P93b
QJ0240-343[3]	2	?	Q	?	1.4	?	T95
MG0414+0534[4]	4	G	Q	?	2.64	Yes	H92
MG0751+2751[4]	4	G	?	0.35	?	Yes	L93a
BRI0952-0115	2	?	Q	?	4.5	?	M92c
0957+561	2	G, C	Q	0.36	1.41	Yes	W79
LBQS1009-0252[3]	2	?	Q	0.87?	2.74	No	H94
HE1104-1805[3]	2	?	Q	?	2.30	?	W93
1115+080	4	G	Q	0.3?	1.72	No	W80
1120+019[3]	2 3? 4?	?	Q	0.6?	1.46?	No	M89
MG1131+0456[4]	2,ring	G	?	?	?	Yes	H88
1208+101[3]	2	?	Q	2.92?	3.80	No	M92a,b
HST12531-2914	4	G	Q?	?	?	?	R95
1413+117	4	?	Q	?	2.55	Faint	M88
B1422+231[4]	4	G	Q	0.64?	3.62	Yes	P92a
HST14176+5226	4	G	Q?	?	?	?	R95
1429-008[3]	2	?	Q	?	2.08	No	H89
MG1549+3047[4]	ring	G	Q lobe	0.11	?	Yes	L93b
CLASS1600+434[4]	2	?	Q	?	1.61	Yes	J95
CLASS1608+656[4]	4	G	Q	.63	1.39	Yes	M95
1635+267[3]	2	?	Q	?	1.96	No	D84
MG1654+1346[4]	ring	G	Q lobe	0.25	1.74	Yes	L89
PKS1830-211[4]	2,ring	?	?	?	?	Yes	J92
B1938+666[4]	4	?	?	?	?	Yes	P92
2016+112[4]	3	G,G	Q	1.01	3.27	Yes	L84
2237+0305	4	G	Q	0.04	1.70	Faint	H85
2345+007[3]	2	G?	Q	?	2.15	No	W82

[1] "G" denotes galaxy; "C" denotes cluster; "Q" denotes quasi-stellar object.
[2] The reference is to the paper reporting the discovery of the lensed nature of the object.
[3] The only evidence for gravitational lensing in this case is the similarity of the optical spectra of the putative images; therefore, the lensed nature of this source might be viewed as not secure.
[4] Radio observations provided the first evidence for gravitational lensing.

mation on the structure and variability of the images.

As more gravitational lens systems are discovered, we find there are

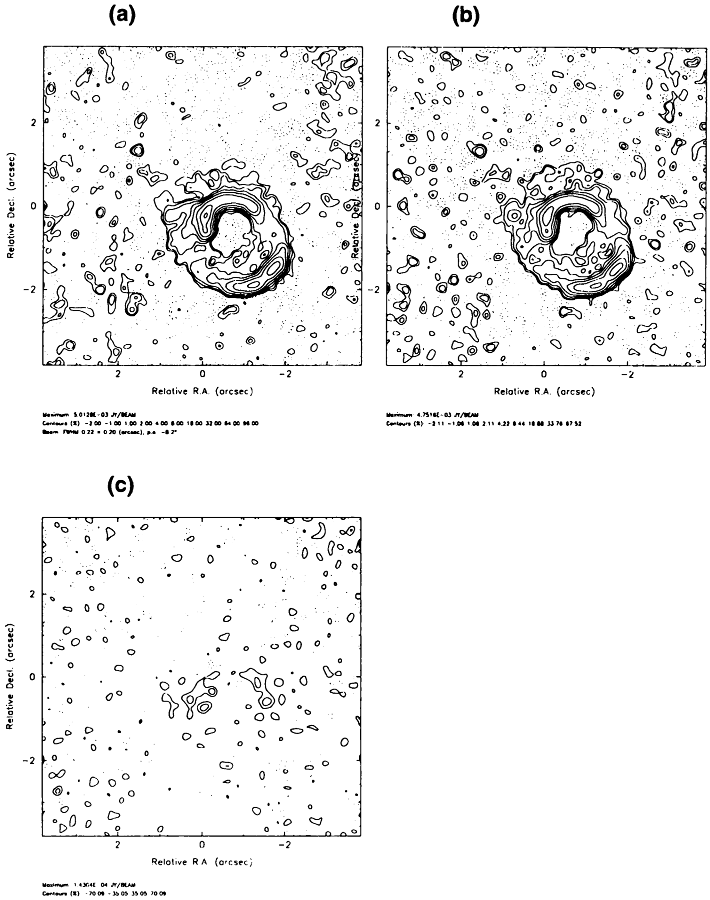

Figure 1. **(a) Radio image of MG1654+1346. (b) Model of MG1654+1346. (c) Image computed from the residual visibilities, giving a measure of the goodness of fit of the model. Reproduced from Ellithorpe, Kochanek and Hewitt 1996.**

systems that are well suited to particular astrophysical applications. In this paper I give examples of two applications: modeling the mass distribution in the lensing galaxy and measuring the angular diameter distance through observing the time delay between a pair of images.

2. Modeling the Lensing Galaxy

The four-image and ring systems, in which there is *extended* structure associated with the background source, provide the most stringent constraints on the model for the mass distribution in the lensing galaxy. Figure 1 shows three images that illustrate the model fitting procedure in MG1654+1346, using the LensClean algorithm initially developed by Kochanek and Narayan

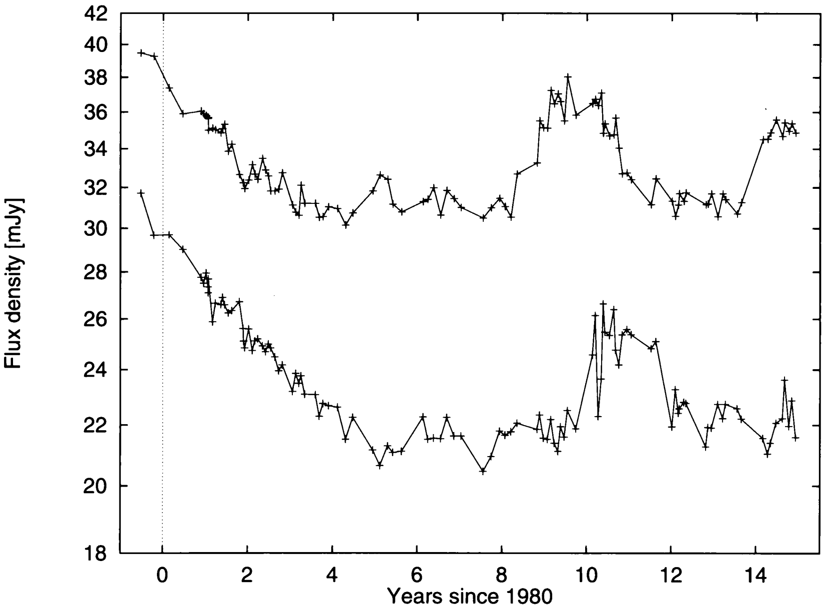

Figure 2. **Radio light curves of the two images of 0957+561 (Haarsma *et al.* 1995).**

(1992), and modified to operate directly on visibility data by Ellithorpe, Kochanek, and Hewitt (1996). There is evidence for dark matter in this system since the mass profile associated with the best fitting model does not trace the light (Kochanek 1995).

3. Measuring Angular Diameter Distance

The measurement of the time delay associated with the propagation of radiation from two images has long been recognized to give a measurement of angular diameter distance (Refsdal 1964, Narayan 1992). This cosmography provides the opportunity to discriminate among cosmological models and to fit cosmological parameters. To date time delays only for 0957+561 and PKS1830-211 have appeared in the refereed literature. Figure 2 shows the most recent results on radio flux density monitoring of 0957+561 (Haarsma *et al.* 1995). A preliminary analysis of these data gives a time delay of 455 ± 40 days. According to the model of Grogin and Narayan (1996), this implies a Hubble constant of 64^{+23}_{-22} km/(sec-Mpc), where the uncertainty is dominated by the uncertainty in the division of mass between the primary lensing galaxy and its surrounding cluster. Converting this into a measurement of angular diameter distance gives $D = 980 \pm 320$ Mpc. Figure 3 shows angular diameter distance as a function of redshift for different cosmological models. Superimposed is the time delay measurement for 0957+561, as well

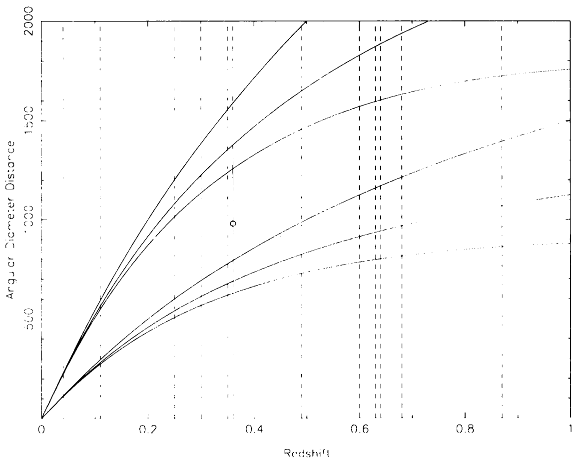

Figure 3. **Angular diameter distance as a function of redshift for (in descending order): H_o = 50km/sec-Mpc, $\Omega = 0$, $\lambda = 1$; H_o = 50km/sec-Mpc, $\Omega = 0$, $\lambda = 0$; H_o = 50km/sec-Mpc, $\Omega = 1$, $\lambda = 0$; H_o = 100km/sec-Mpc, $\Omega = 0$, $\lambda = 1$; H_o = 100km/sec-Mpc, $\Omega = 0$, $\lambda = 0$; H_o = 100km/sec-Mpc, $\Omega = 1$, $\lambda = 0$. The derived value for 0957+561 is plotted. The vertical dashed lines represent the lens redshifts tabulated in Table 1.**

as vertical dotted lines showing the distribution of the known lenses on this diagram. Perhaps in the future such a plot will display many gravitational lens measurements of angular diameter distance.

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