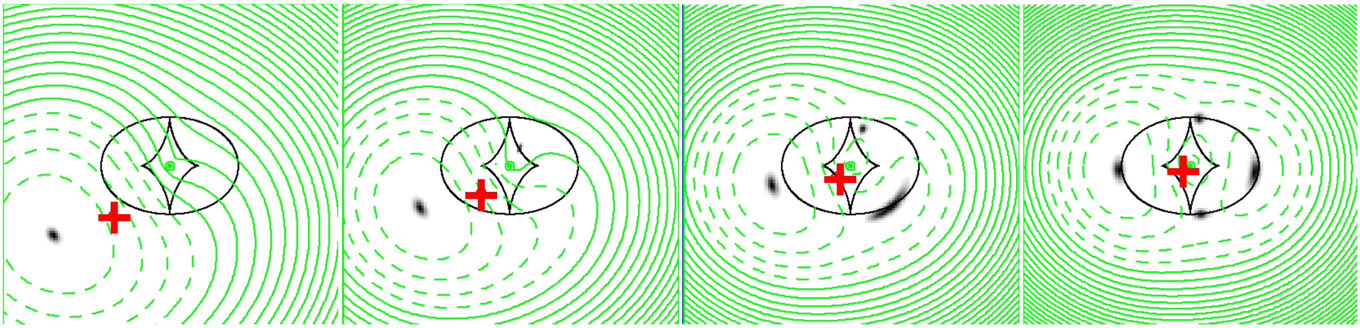

Figure 3: This figure shows the formation of images by a lensing galaxy as the source, of which the undeflected position is indicated by a cross, moves progressively closer to the line of sight. At large distances (left panel) the image of the source, shown in greyscale, is distorted but not multiply imaged. The green contours show the Fermat surfaces, which are loci of points requiring equal travel times for light rays that pass through them, and it can be seen that a single image forms at the extremum. The inner (diamond-shaped) and outer (elliptical) lens caustics are also shown in all four panels. As the source crosses the outer caustic of the lens (panel 2) the Fermat surfaces pucker and a second image is formed. As the source crosses the inner caustic (panel 3) a new double image is formed, which separates to a more symmetrical four-image structure (right panel) as the source and the galaxy become more aligned. An odd image forms near the centre of the galaxy, but does not appear in this figure due to strong demagnification. [A colour version of this figure appears in the CD-ROM version of this chapter].

2. LENS SEARCHES

2.1 Serendipity: the first lens system

The first gravitational lens system was discovered in 1979 by a combination of systematic observing technique and good fortune. In 1972/73 the University of Manchester's Mk1A (now Lovell) 250-foot radio telescope at Jodrell Bank was used to conduct a radio source survey at a frequency of 966 MHz of a strip of northern sky. The Jodrell Bank group were particularly interested in quasars, which are now known to involve violent ejection of synchrotron-emitting radio plasma from a small region (∼1 parsec) surrounding a large central black hole in the centre of a distant galaxy. That these regions could be very small had been demonstrated by interferometric observations in the 1960s, using single-baseline interferometers involving the MkI telescope at Jodrell Bank together with other smaller telescopes at successively greater distances. VLBI in the 1970s showed that these regions could be milliarcseconds in size.

It was necessary to improve on the accuracy of the survey radio positions in order to make the optical identifications required to separate the quasars from other objects. An interferometer consisting of the Jodrell Bank Mk1A and Mk2 (∼25 m) telescopes was used for this purpose giving positions accurate to $\sim 1''$ for compact objects. There were some fields, however, for which the interferometer did not give unambiguous results; either the target was very extended and resolved by the interferometer or there was more than one radio source in the telescope beam. Such fields were reobserved with the NRAO 300-foot radio telescope operating at a frequency of 5 GHz. One of the fields with multiple sources in the MkIA beam was close to the galaxy NGC3079. *Walsh [1989]* describes what happened next; the NRAO 300-foot radio observations *[Porcas et al., 1980]* found a weak source, 0957+561, below the survey limit in addition to (and initially, instead of) the strong source NGC3079 with which it had been confused. 0957+561 would never have made it into the survey had it not been for this coincidence. When optical identifications were undertaken, and optical spectroscopy obtained to determine the redshift, the radio source was found to correspond to two optical components, about 6 arcseconds apart. It was in principle possible that this represented a chance coincidence of two quasars. However, the optical spectra of the two quasars were virtually identical, a fact which argued strongly against the coincidence hypothesis – resulting in the first claim *[Walsh, Carswell & Weymann 1979]* of the observation of a multiple image gravitational lens system. Confirmation in the form of the double nature of the radio source *[Pooley et al. 1979]* and the presence of a lensing galaxy *[Young et al. 1980]* soon followed, and the observational gravitational lensing era was born.

2.2 Systematic searches

Systematic searches for lenses soon followed. Many of these have relied on the same brute-force principle — namely, the imaging of many background sources in order to pick out the small fraction (now known to be about 1:500) which have lensing galaxies sufficiently close to the line of sight to produce the multiple imaging characteristic of a lens system. A full catalogue of known galaxy-mass lenses and a gallery of Hubble Space Telescope images is given on the CASTLeS (CFA-Arizona Space Telescope Lens Survey) website *[Kochanek et al., 2001]*.

The early history of lens searches is described in detail in chapter 2 of *Schneider, Ehlers & Falco [1992]*. The first major survey, the MIT-Greenbank (MG) Survey, was carried out at radio wavelengths by the group based at MIT [*Bennett et al., 1986; Lawrence et al., 1986; Hewitt et al., 1988]* and consisted of high-resolution observations with the VLA[3] of sources picked up with lower resolution using the 300-foot Green Bank radio telescope. Five lenses were eventually discovered by this survey, some including Einstein ring images which arise when parts of an extended radio source lie exactly behind the lensing galaxy. *Lehár et al. [2001]* describe a more efficient new survey which examines extended radio structures coincident with optical identifications of extended galaxies which may be lensing them[4].

Early optical searches [*Crampton, McLure & Fletcher, 1992; Surdej et al., 1993; Jaunsen et al., 1995; Kochanek, Falco & Schild, 1995]* discovered a few lenses between them, although the surveys were limited to the resolution available to ground-based optical telescopes. This resolution is typically about $1''$, comparable with the Einstein radius of galaxy-mass gravitational lens systems which encloses only the central region of a typical galaxy. This resolution is barely adequate for detection of the majority of systems. With the coming of the HST, routine high-resolution ($0.''1$) optical imaging capable of detecting lensed images with sub-arcsecond separations was also possible. A "snapshot" survey was instigated *[Bahcall et al., 1992; Maoz et al., 1992]* which with its successors has produced

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[3] Very Large Array, an array of 27 radio telescopes in New Mexico, and part of the U.S. National Radio Astronomy Observatory

[4] When the source size becomes comparable to the Einstein radius the lensing probability depends both on the lens and source properties.

12 lenses to date. Many authors have pointed out *[Mortlock & Webster, 2000; Richards et al., 1999]* that future optical spectroscopic programmes such as the Sloan Digital Sky Survey *[York et al., 2000]* will discover many more gravitationally lensed quasars.

The most extensive lens survey has been the JVAS/CLASS (Jodrell Bank-VLA Astrometric Survey *[King et al., 1999]*/ Cosmic Lens All-Sky Survey *[Jackson et al., 1995; Myers et al., 2001]* based at Jodrell Bank Observatory, University of Manchester, UK and involving NFRA, Dwingeloo and the University of Groningen (Netherlands) and Caltech, NRAO and the University of Pennsylvania (USA). This radio survey has discovered 18 lenses to July 2001 (Fig. 4), and has contributed the largest homogeneous lens sample of all. It differs from earlier radio surveys in that it concentrates on compact, flat-spectrum radio sources rather than the (typically) extended, steep-spectrum objects studied in the MG survey. Although Einstein rings are therefore less common, the JVAS/CLASS methodology makes lenses much easier to recognise reliably – which has important advantages for cosmological investigations (section 4).

JVAS/CLASS selects flat-spectrum sources from existing low-resolution radio catalogues of the northern sky, which are then observed at $0\farcs2$ resolution with the VLA. Most flat-spectrum radio sources are the synchrotron-self-absorbed cores of active galaxies, and are intrinsically very small ($\leq$1 mas). This means that any source in which the VLA reveals structure on arcsecond scales becomes a candidate gravitational lens unless its structure is inconsistent with the lensing hypothesis (usually because the secondary component is resolved). 97% of objects are rejected at this stage. Still higher resolution observations using the longer-baseline MERLIN array[5] must, however, be undertaken for the remaining 3% in order to distinguish structure characteristic of gravitational lensing from "normal" source structure, for example collimated radio jets ejected from the compact core. This procedure rejects 80% of the remaining lens candidates *[King et al., 1999]*, leaving only a few targets for the final high-resolution radio observation to be done with very long baseline interferometers, in particular the VLBA[6], to confirm them as lens systems. Reliable lens confirmation is thus achieved by radio means alone.

JVAS/CLASS is a northern sky survey. Recently a number of groups have begun to apply the same method to the southern sky, although a major handicap there is the lack of long-baseline radio interferometers in the southern hemisphere; the lack of a southern MERLIN and the VLA's southern declination limit of $\sim -40°$ makes the process particularly difficult. Nevertheless, the first successes are being achieved by these groups *[Winn et al., 2000; Winn et al., 2001]*.

2.3 The current position: radio and optical searches

The CASTLeS website currently (2001 July 01) lists 63 secure, or reasonably secure, cases of gravitational lensing by galaxy-mass objects. There are approximately equal

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[5] The MERLIN array is an interferometer system of six radio telescopes in England *[Thomasson, 1986]* based at Jodrell Bank Observatory, University of Manchester

[6] The Very Long Baseline Array *[Kellermann & Thompson, 1985]* is an interferometer system consisting of 10 radio telescopes throughout the continental USA, Hawaii and Puerto Rico, and is part of the US National Radio Astronomy Observatory

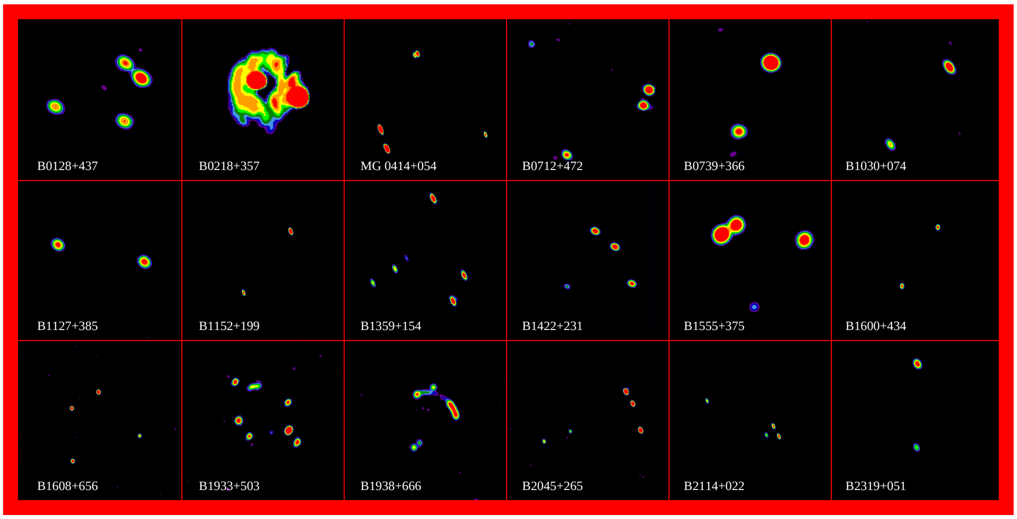

Figure 4: Eighteen of the JVAS/CLASS survey lenses, observed with MERLIN. Note the predominance of simple 2-image and 4-image systems. Some lenses, however, have Einstein rings (e.g. JVAS B0218+357) and arcs (e.g. JVAS B1938+666); Others have more than four images, either due to multiple background sources (CLASS B1933+503) or multiple deflectors (CLASS B1359+154). It is expected that the JVAS/CLASS survey will produce several more lenses when it is completed in 2001.

numbers of lenses discovered by radio and optical searches. However, radio searches have a number of distinct advantages, the first three of which are important in allowing sample completeness and clean statistics:

- *Lens recognition.* Many radio sources exist which have intrinsically simple structures when observed with moderate dynamic range and $0\farcs2$ resolution. This means that one can hope to identify all multiple-image lens systems in any given sample of sources, unlike the case of optical searches where galaxies with intrinsically complex structures can be lensed to give extended images which are difficult to recognise.

- *Resolution.* The initial search with the VLA can be made with a consistent resolution of $0\farcs2$ or better, which is difficult to achieve optically without large expenditure of scarce HST time. This is important given the small scale ($0\farcs5 - 2''$) of most single-galaxy lens systems.

- *Freedom from obscuration by dust.* By their nature, lens systems involve passage of light through the medium of the lensing galaxy. In some cases there is evidence for considerable reddening, which makes lensed images difficult to recognise in optical pictures, and requires infrared imaging at $2\,\mu$m before the dust becomes more transparent. Radio studies can therefore be more complete than those in the optical, in the sense of identifying all lenses within any sample.

- *Variability.* Many radio sources are variable and high-resolution radio imaging allows us to track the variability of individual components. As we shall see in section 4, this allows us to derive the Hubble constant.

3. LENS MODELLING

3.1 How models are made

The aim of lens modelling is to use observations of gravitational lens systems to determine the mass distribution of the lensing galaxy or galaxies, both for its intrinsic astrophysical interest (see Section 2) and in order to exploit the lens systems for other investigations. Quite frequently a lens mass model is also an important step in confirming a lensed system. No other technique tells us so much about the mass distributions of high-redshift galaxies.

The modelling process consists of a mapping between the source plane, which contains the lensed object, and the observed image plane. In the simplest case, that of a lensed point source, we demand of a "good model" that the observed image positions should all map back to the same point on the source plane, given the model parameters which describe the lensing galaxy. In addition, the observed flux ratios of the images should agree with the relative magnification of the images required by the model.

In many cases there are only very limited constraints on the mass model. Free parameters in the model typically include the position of the source and the position, mass, ellipticity and axial ratio of the mass model for the lens. The constraints are obtained from the image positions and flux densities, including VLBI imaging of milliarcsecond-scale structure, together with the galaxy position (if this is known, usually via an HST image). VLBI imaging has also been made in polarization *[Patnaik et al., 1999]* giving additional constraints and also demonstrating clearly the expected mirror symmetry between different images in the lens system. In many cases, however, the observations leave few degrees of freedom for constraining the detailed mass profile of the galaxy; as we shall see a large range of mass distributions is consistent with the observational constraints. In general, four-image lens systems are more valuable for mass modelling, because of the greater number of constraints available from the lensed images.

An interesting and more radical approach has been taken by *Saha & Williams [1997]*. Instead of using parametric models, they perform pixellated free-form fits to recover the shape of the lensing galaxy, subject to only a few constraints such as rotational symmetry and monotonically decreasing mass density with radius. Results consistent with the data are obtained in which the nature of the lensing galaxy is highly degenerate with the Hubble constant H_0 (see section 4). An intermediate position is taken by *Trotter, Winn & Hewitt [2000]* who decompose the potential by multipole Taylor expansion. Future work in lenses with more observational constraints may diminish the freedom allowed by such models.

3.2 Types of lensing galaxy

Because of their generally larger masses and high central concentration, giant elliptical galaxies are the major contributors to gravitational lensing *[Turner, Ostriker & Gott, 1984]*. *Kochanek et al. [2000a]*, *Lehár et al. [2000]* , and *Keeton, Kochanek & Falco [1998]* in a study of lensing galaxies with the HST conclude that they are indeed generally elliptical galaxies which lie on the so-called "fundamental plane"; this is a locus in the space defined by the velocity dispersion, the surface brightness within effective radius and luminosity, in which elliptical galaxies congregate *[Dressler et al., 1987]*. However, a few lensing galaxies have been shown to be spiral systems (e.g. JVAS B0218+357 *[Wiklind & Combes, 1995]*; CLASS B1600+434, *[Jaunsen & Hjorth, 1997]*).

3.3 Types of mass profile

As previously suggested, we do not have a very good idea of the mass distributions of galaxies at cosmological redshifts. Lacking such knowledge, we can ask instead about the light distributions. For nearby elliptical galaxies, reasonable fits to the light distributions are given by the de Vaucouleurs "$r^{1/4}$" law for the surface brightness Σ: $\Sigma(r) = \Sigma_0 \mathrm{exp}\left(-7.67((r/r_0)^{1/4} - 1)\right)$ where r_0 and Σ_0 are free parameters and r is the distance from the centre of the galaxy. For spiral galaxies, the "exponential disk" model, $\Sigma(r) = \Sigma_0 e^{-r/r_0}$, appears to fit the data better. However, neither of these parametrizations works particularly well for the central regions of high-redshift galaxies imaged by the HST. *Faber et al. [1997]* suggest instead a "cusp" distribution of light that follows $I \propto r^{-\gamma}$, with $\gamma \leq 0.3$, for the inner part of the galaxy and a steeper power-law in the outer parts; this distribution has recently been adopted for mass modelling by e.g. *Muñoz et al. [2001]*.

Some of the distributions proposed for the projected surface mass density Σ and corresponding deflection angles α include the following (see also Fig. 2):

- the "singular isothermal sphere (SIS)", for which $\Sigma = \Sigma_0/r$ and $\alpha = \text{constant} \times$ `sign` (θ), where Σ is the projected surface mass density;
- the "singular isothermal ellipsoid (SIE)", which is identical to the SIS except for different scale lengths along the x and y axes;
- the "pseudo-Jaffe model" *[Jaffe, 1983; Muñoz, Kochanek & Keeton, 2001]* for which $\Sigma = k((r^2 + r_s^2)^{-1/2} + (r^2 + a^2)^{-1/2})$, where k, r_s and a are constants;
- the "Navarro, Frenk & White" profile *[Navarro et al., 1996; Bartelmann 1996]*, for which the three-dimensional density is given by $\rho = \rho_s(r_s/r).(1 + r/r_s)^{-2}$, where ρ_s and r_s are constants.
- the generic cusped model, corresponding to $\rho_s r^{-\gamma} a^n (r^2 + a^2)^{(\gamma-n)/2}$, where additional constants γ and n are introduced; several other models are special cases of this distribution *[Muñoz, Kochanek & Keeton, 2001]*.

A full catalogue of these and many other models is given by *Keeton [2001]*.

In practice, few lens systems provide sufficient constraints to distinguish between the various mass models. This is particularly true for lenses in which companion galaxies or galaxy clusters are present, whose mass field provides an extra contribution to lensing (e.g. *Hogg & Blandford [1994]*). There may also be a contribution from the shape of the dark matter halo of the primary lensing galaxy *[Keeton, Kochanek & Seljak, 1997]*. Whatever its origin, nearly all models which fit the data even tolerably well require the parametrisation of some external perturbation (e.g. *Cohn et al. [2001]*).

For a good model, we therefore need extra information. This can be provided by VLBI imaging of the lensed images; the higher resolution can reveal extra components in the