3. How do we find them?

Searches for galaxy-mass gravitational lenses

The first gravitational lens, 0957+561, was found serendipitously. Soon after, however, serious directed searches began.

The usual way to search for gravitational lenses is a brute-force approach, and it is to look at very large numbers of background objects with a view to picking out the very small fraction which happen to have lenses close to the line of sight. Typically, for background objects such as quasars which lie at vast distances, about 0.2% of objects show the multiple imaging we expect from a gravitational lens system. Because of this low success rate, lens surveys are a formidable undertaking; a survey carried out by Jodrell Bank and collaborating institutions (CLASS, to be described later) has taken 10 years to complete. Over 20 years after the first lens was discovered, only 70 galaxy-mass lens systems are known. A complete list (known as CASTLeS) of lenses discovered by all published surveys to date, including HST pictures, is maintained by the gravitational lens group at the Center for Astrophysics at Harvard University in Boston, Massachusetts.

Search strategies

For a gravitational lens survey, several things are ideally needed:

1. **High and consistent resolution.** Remember that the typical Einstein radii of these lensed systems is about 1 arcsecond, so the necessary angular resolution of the observations has to be better than this. Ground-based optical observations are limited by the effects of atmospheric turbulence ("seeing") to about 0.5-1 arcseconds at very good sites. In practice, many successful searches have been done using the Hubble Space Telescope with a resolution of about 0.05 arcseconds. The other alternative is to use arrays of radio telescopes known as interferometers such as MERLIN which have similar resolving power to the HST.
2. **A suitable population of background objects.** Ideally the background objects should have high redshift - i.e. lie as far away as possible. This increases the chance that a foreground galaxy will happen to be close enough to the line of sight to produce gravitational lensing. In practice, the sources usually used are quasars. These objects radiate large amounts of energy in the optical, and about 10% of them are also powerful emitters of radio waves.
3. **Insensitivity to obscuration.** A particular problem with optical surveys is that optical radiation can be obscured by dust. Since by definition a gravitational lens system involves a background object seen very close to an intervening galaxy, lens systems are particularly susceptible to this effect. Radio waves, on the other hand, pass through without being affected, see Figure 3.1.

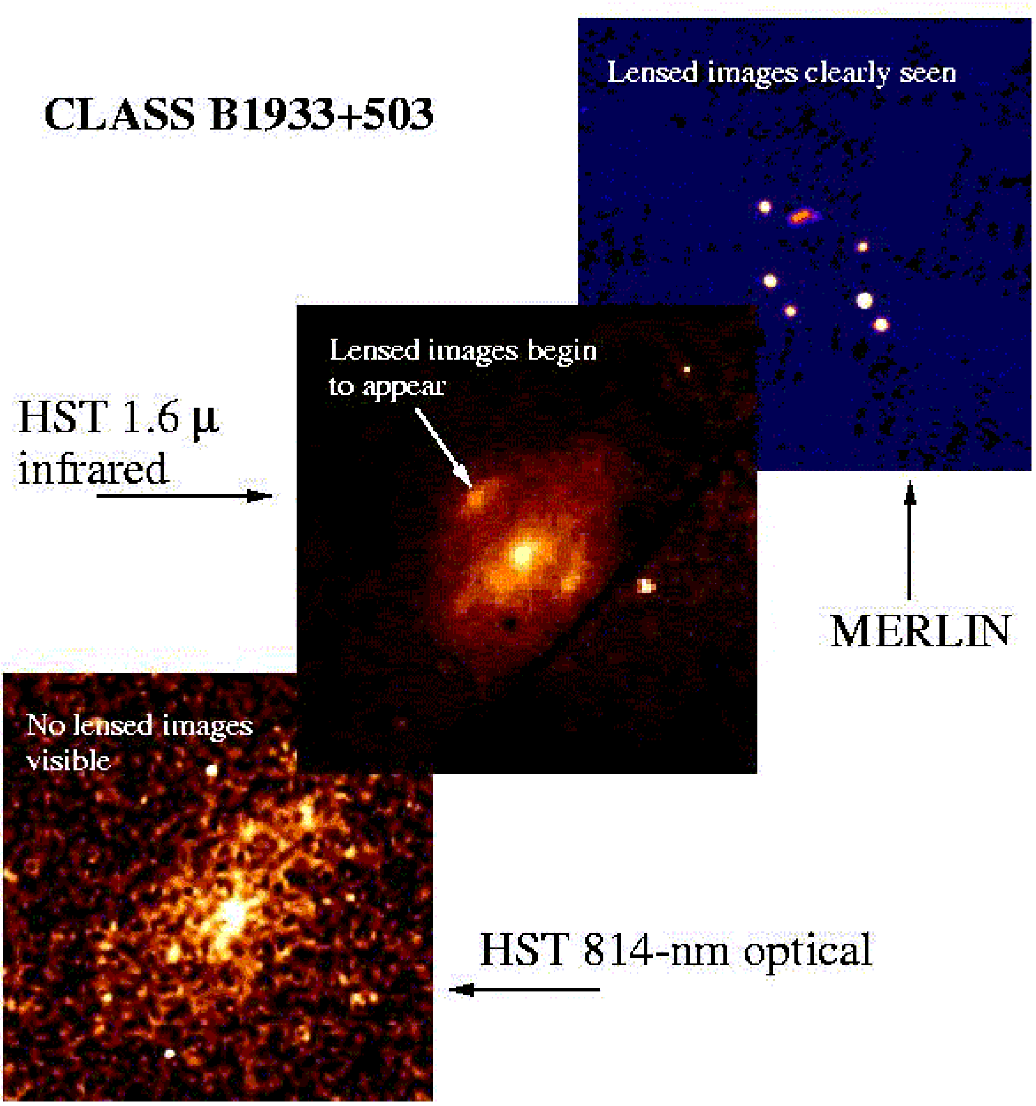

Figure 3.1. The gravitational lens CLASS 1933+503. This illustrates the advantages of radio surveys. In the Hubble Space Telescope optical picture, only the lensing galaxy is seen. The lensed images of the background source are extremely faint, either because the source is intrinsically very faint in the optical, or because of obscuration of the optical light during passage through the lensing galaxy, or both. In the infra-red picture, again taken with the HST, the lensed images begin to appear. In the MERLIN radio picture, the lensed images can be clearly seen although here the lensing galaxy, not being a radio source, disappears. Similar effects can be seen in the montage of 0957+561 presented in section 1.

Early surveys

After the discovery of the first gravitational lens, systematic searches got under way. In the radio, a collaboration between the Massachusetts Institute of Technology (MIT) and Greenbank Observatory in West Virginia looked carefully at several thousand radio sources. They found a number of lenses, including several Einstein ring images. Figure 3.2 shows a montage of HST pictures of some of their discoveries, from the CASTLeS website.

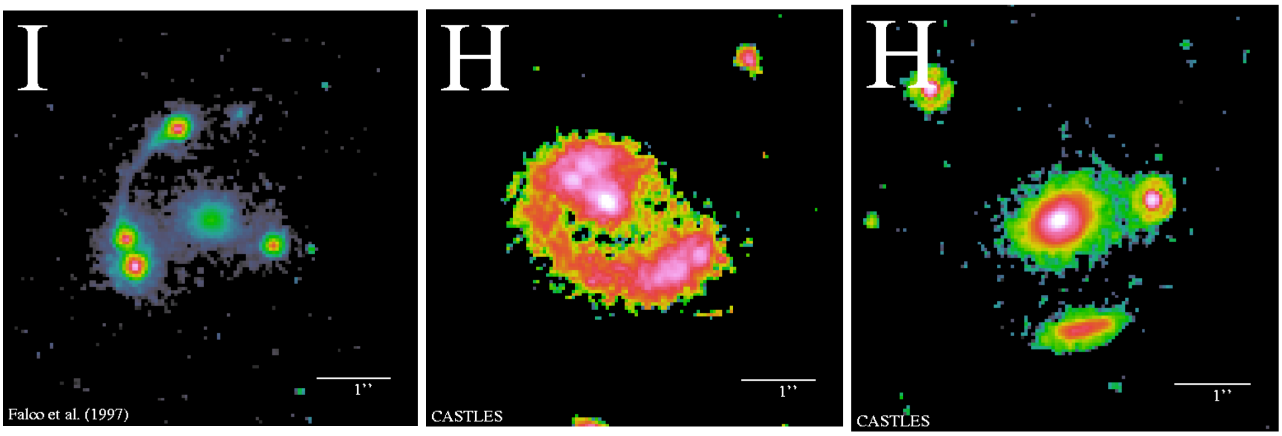

Figure 3.2. Three of the MG (MIT-Greenbank) survey lenses (click on images to get larger scale view). In the system on the left, a foreground galaxy (seen at the centre) lenses a background object into four images. In the middle system, extended radio structure in the background object lies directly behind the foreground galaxy and forms an Einstein ring around it. In the third system, a central galaxy once again forms a four-image system; the extended arc in the south is the result of the partial merging of two of the images.

Other surveys began at about the same time. With the launch of the Hubble Space Telescope in 1990, a long-term survey began working at optical wavelengths. This has so far discovered about a dozen gravitational lenses.

A case study: the CLASS survey

A large survey, known as the Cosmic Lens All Sky Survey (CLASS) has been carried out over the last 10 years by a collaboration of Jodrell Bank Observatory (University of Manchester), and institutes in the Netherlands (Leiden Observatory, Dwingeloo Radio Observatory and Groningen University) and the USA (Caltech, the National Radio Astronomy Observatory and the University of Pennsylvania).

CLASS is a radio survey which uses the Very Large Array (VLA) in New Mexico, USA. First we used the VLA to look at 16,545 radio sources at an observing wavelength of 3.6cm.

Figure 3.3. The Very Large Array in New Mexico. Photo from the National Radio Astronomy Observatory, USA. This instrument is reconfigurable, and the antennas can be withdrawn or extended along railway tracks to give different baseline lengths. The photo shows the smallest configuration; the longest configuration (maximum baseline 36 km) was used for the CLASS observations to give maximum angular resolution.

1. The angular resolution of observations obtained at an observing wavelength **L** with an interferometer array of maximum dimension **d** (both measured in the same length units) is **L/d** radians. Calculate the resolution, in arcseconds, of the CLASS VLA observations. Is this a suitable resolution for gravitational lens searching?

The survey targeted a class of radio source known as **flat-spectrum radio sources**. "Flat spectrum" implies that they emit approximately the same flux over a range of radio frequencies.

In astrophysical terms, this means that they are very compact. The physics of the emitting regions is such that only compact radio-emitting regions produce flat radio spectra; less compact regions produce radio emission which diminishes at shorter wavelengths. From our point of view, compact sources are useful because they make gravitational lensing easy to recognise; the intrinsic object is just a point and any structure detected in the VLA observations automatically labels the source as a potential gravitational lens.

This is, however, not the end of the story. 97% of objects in the VLA observations are point sources (showing no structure which would suggest multiple images) and can be discarded immediately from the search. However, the remaining 3%, as well as gravitational lenses, contain objects with some intrinsic radio structure. This happens when the core of the quasar ejects some material which can be seen at radio wavelengths, making the source appear extended.

In order to separate genuine cases of lensing from intrinsic structure, we perform observations at higher resolution using the MERLIN array at 6cm, see Figure 3.4. This has a maximum baseline of 220km.

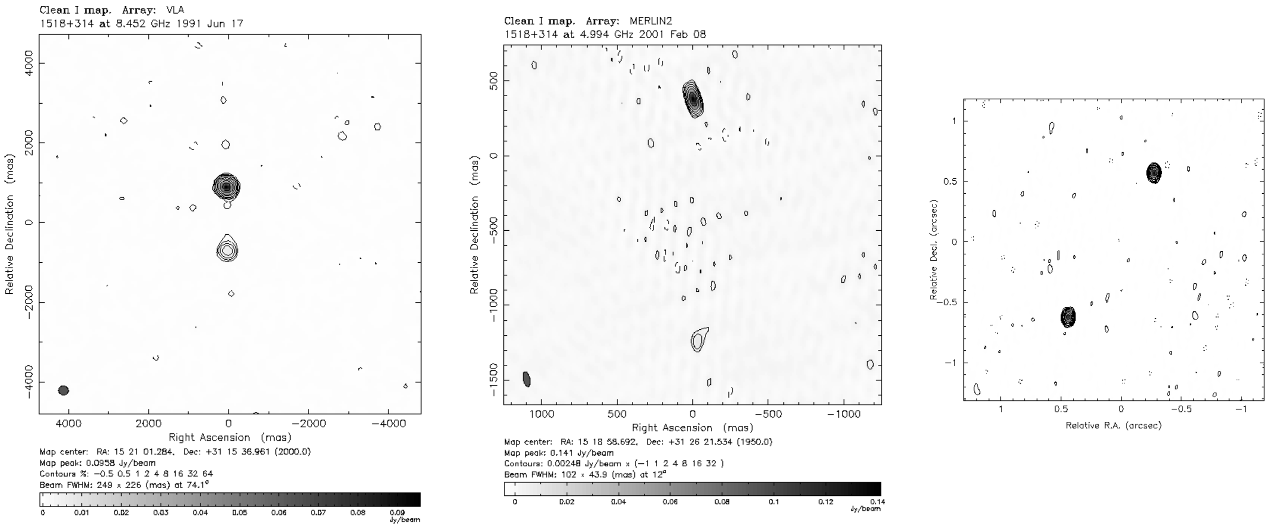

Figure 3.4. Here we show an example of a source which looked promising as a candidate with the VLA (left) but was ruled out by higher-resolution observations with MERLIN (middle, showing the central part of the VLA image - note the scales on the axes) - click on the images to view larger-scale versions. If lensing really is occurring we would expect two point sources to be seen; here, however, it is clear that the second component is larger and 'fluffier' than the first. This is due to intrinsic structure - a lobe of radio plasma is being ejected from the compact core. We also show an example of a source (right) which did turn out to be a gravitational lens. Here the MERLIN observation still shows two compact cores. Further observations with the HST also showed the lensing galaxy.

2. Calculate the resolution of the MERLIN observations and confirm that they have a higher resolution than the VLA observations.

The MERLIN observations reject about 80% of the remaining candidates by showing detail in the extended radio structure. The essential point here is that although lensing can magnify images, and thereby change the total brightness of images with respect to each other, the **surface brightness**, or brightness per unit area on the sky, remains constant. If we observe with higher resolution, therefore, and find that one of the images becomes weaker and more nebulous whereas the other remains bright and pointlike, we can deduce that the images cannot be gravitationally lensed versions of the same background object.

The final stage is to observe the remaining candidates not rejected by MERLIN, at still higher resolution using the U.S. Very Long Baseline Array, which has a resolution of a few milliarcseconds. The same test based on surface brightness arguments is applied to the VLBA images. Finally, the Hubble Space Telescope is used for confirmation of remaining lens candidates. At this stage, optical pictures with the HST typically show the lensed images, together with the lensing galaxy.

Figure 3.5 shows the gravitational lenses discovered by the CLASS survey. The survey has just been completed and all but four of the lenses have been confirmed and published. Note that most are the simple 2-image or 4-image configurations that you saw in the lens simulations in the first section of this course.

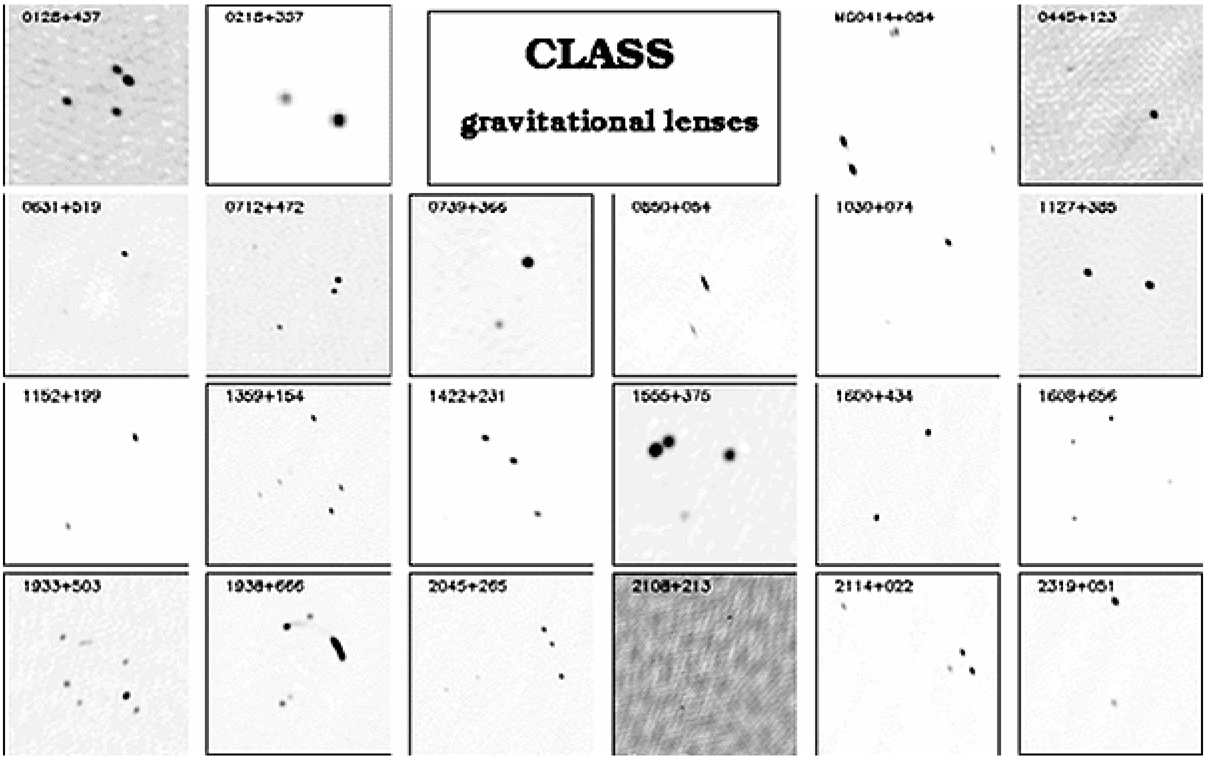

Figure 3.5. Gravitational lenses discovered by the CLASS survey (click for larger scale image). B2108+313 is a very faint double source (the weaker component is just visible towards the bottom left).

Try to reproduce the four-image configurations seen in the observations of Fig. 3.5 using the gravitational lens simulator introduced in the previous section. Try in particular to obtain the interesting configurations seen in 4-

image lenses such as B1422+231 (move the source around the edges of the inner diamond caustic for these effects) - a separate image of B1422+231 is shown in Figure 3.6 which reveals the position of the fourth image.

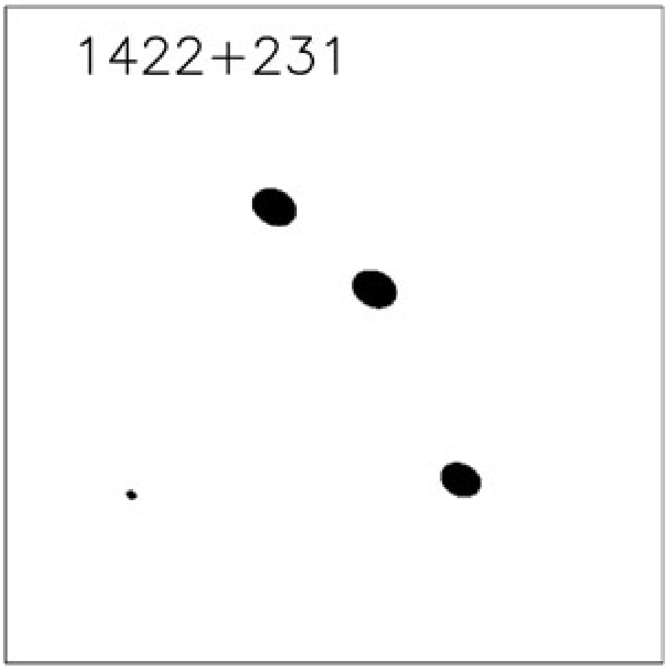

Figure 3.6. High contrast image of B1422+231 showing all four images.

3. What do you think is going on in 1938+666?

In the next section we will see how gravitational lensing can be used to probe the distribution of matter in the lensing galaxy.

Answers to questions

1. The angular resolution of observations obtained at an observing wavelength **L** with an interferometer array of maximum dimension **d** (both measured in the same length units) is **L/d** radians. Calculate the resolution, in arcseconds, of the CLASS VLA observations. Is this a suitable resolution for gravitational lens searching?

Answer to question

0.21 arcseconds; yes.

The wavelength divided by the distance is 0.036/36000.0 (remembering to convert both *L* and *d* to metres), or 10^{-6} radian. This corresponds to 0.21 arcseconds, which is smaller than the image splittings of most lenses and therefore enough for lens searches.

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2. Calculate the resolution of the MERLIN observations and confirm that they have a higher resolution than the VLA observations.

Answer to question

0.056 arcseconds

L/*d* in this case is 0.06/220000.0 radians, hence converting to arcseconds we have 0.06x57x3600/220000 = 0.056 arcseconds which is almost 4x larger than the VLA resolution of 0.21 arcsec.

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3. What do you think is going on in 1938+666?

Answer to question

There are two sources

The background source is a galaxy which is ejecting two radio components either side of the galaxy. One radio component is lensed into four images: the arc structure together with one of the images at the bottom. The other is doubly imaged, forming one of the other bottom images together with the point image at the top. The Hubble Space Telescope picture shows the Einstein ring associated with the image of the extended background galaxy. See our press release for more details.