# 12.3: Lensing by Extended Mass Distributions

## Learning Objectives

- You will understand that galaxies and clusters of galaxies can act as gravitational lenses.
- You will understand that many astrophysical lenses are complex in nature. You will understand that lensing suggests that most of the mass of galaxies and galaxy clusters is dark.
- You will understand that lenses provide an independent prediction of dark matter, distinct from that based upon Newtonian dynamics and the motions of stars, gas and galaxies.

## What Do You Think: Gravitational Lensing With Galaxies

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### 12.3.1: Extended Lenses Provide More Complex Patterns of Images

In the previous sections we considered gravitational lenses that are point masses. These would be objects like stars or black holes, objects whose mass is relatively small and compact. Other kinds of gravitational lenses exist: those whose mass is distributed over large volumes of space. Objects like galaxies and clusters of galaxies are examples of extended lenses. In this section, we will see how these extended lens systems differ from point lenses, and we will explore what they can tell us about the Universe.

In essence, extended masses are collections of point masses; galaxies are collections of stars, with some amount of gas mixed in. However, the simplest treatment of these systems assumes that they are smooth distributions of mass. It is generally not necessary to consider the stars and gas clouds individually if we want to understand the behavior of a galaxy as a whole. Instead, a distribution of mass is assumed, the expected image pattern for that assumption is computed, and then that prediction is compared to the lenses we see in the sky. One of the simplest assumptions to make is that the stellar velocities (or velocity dispersions in an elliptical galaxy) of the galaxy are constant. Indeed, this is a property generally seen in galaxies anyway, though if we prefer, other velocity structures can be used instead. In any event, the velocity of material in a galaxy is related to the mass distribution of that galaxy.

The first gravitationally lensed object observed was the so-called Double Quasar, detected in 1979. The system shows what appears to be two quasars separated by a mere six arcseconds in the sky. The quasars are peculiar in that they have nearly identical spectra. The similarity is so great that it caused astronomers Dennis Walsh and Robert Carswell of Great Britain, and American Ray Weymann, to suggest that the pair were actually two images of the same quasar. They surmised that the quasar was being lensed by an intervening and unseen galaxy. Their interpretation was confirmed over the next several years by several other teams who used radio observations to make detailed images of the quasar system. The intervening lens was also found and studied. It turned out to be a galaxy cluster, not a single galaxy. Figure 12.9 shows an image of the Double Quasar.

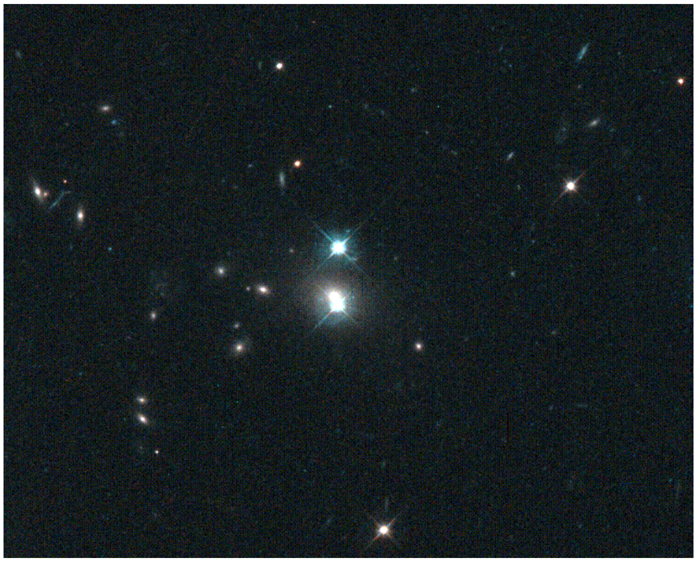

Figure 12.9 This image shows two apparently identical quasars separated by just a few arcseconds in the sky. In 1979, a team of astronomers suggested that we are actually seeing a single quasar that is being lensed by a galaxy along the line of sight. The system is known as the Double Quasar, or as QSO 0957+561 A and B. A bright galaxy, part of the cluster responsible for the lensing, is seen almost on top of the B image of the quasar. Credit: NASA/ESA/HST/WFPC2/George Rhee

Since 1979, many more examples of gravitational lenses have been found. They are especially conspicuous in the deep, high-resolution images taken with the Hubble Space Telescope and the larger ground-based telescopes using adaptive optics to correct atmospheric distortions. Most of these lenses are far more complex than the Double Quasar.

As we have discussed, the mass distribution in a lens affects the distribution of images seen in that system. For the Double Quasar, the mass distribution in the lens is relatively simple, but in other systems that is not the case. Careful study of the image distribution around a lens can provide important information about the total mass of the lens as well as its distribution. The lens geometry—the relative positions of the source, lens, and observer—will also have an effect on the distribution of the images seen. Sometimes it can be difficult to disentangle the mass distribution and geometry effects from each other, but rigorous analysis of the images often removes any such confusion, at least when the lens effect is strong enough to produce many images over a large region.

As we have seen, point sources give two images aligned with the lens itself. In an extended source there can be more than two images. Figure 12.10 shows a quasar that is lensed by a galaxy, producing four images. Images are only co-linear with the lens if the mass distribution of the lens has circular symmetry in the plane of the sky. That is not generally the case for galaxies or galaxy clusters. Figures 12.11 and 12.12 show examples of gravitational lensing by galaxy clusters. The type of image pattern seen in Figures 12.9–12.12 is called strong lensing because the lensing distortions (multiple arced images) are pronounced and easy to identify.

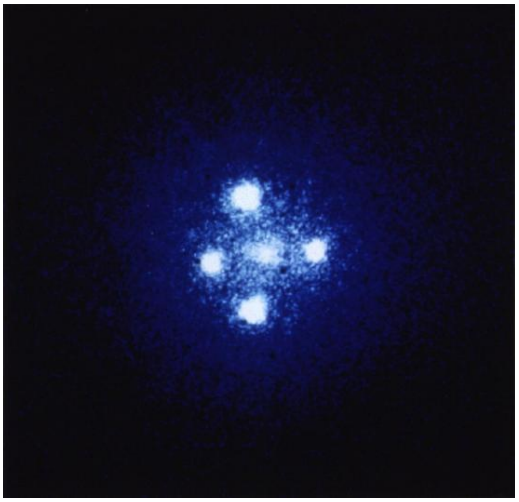

Figure 12.10 For the right mass distribution and geometry it is possible to observe four quasar images rather than two. Such an image is known as an Einstein Cross. Credit: NASA/Hubble Space Telescope

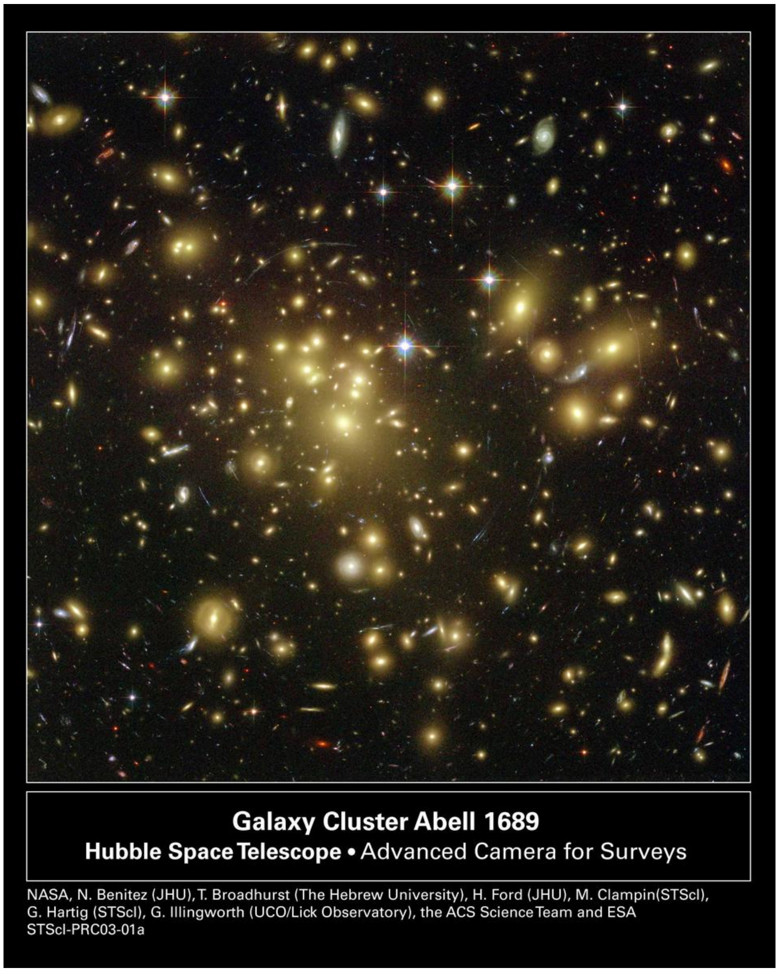


Figure 12.11 Many arcs are seen in and around this galaxy cluster, called Abell 1689. These arcs are background galaxies magnified and distorted by the mass within the cluster. The fact that the arcs all seem to be concentric indicates that the mass of this cluster is fairly symmetrically distributed around the central galaxy. Credit: NASA/Hubble Space Telescope

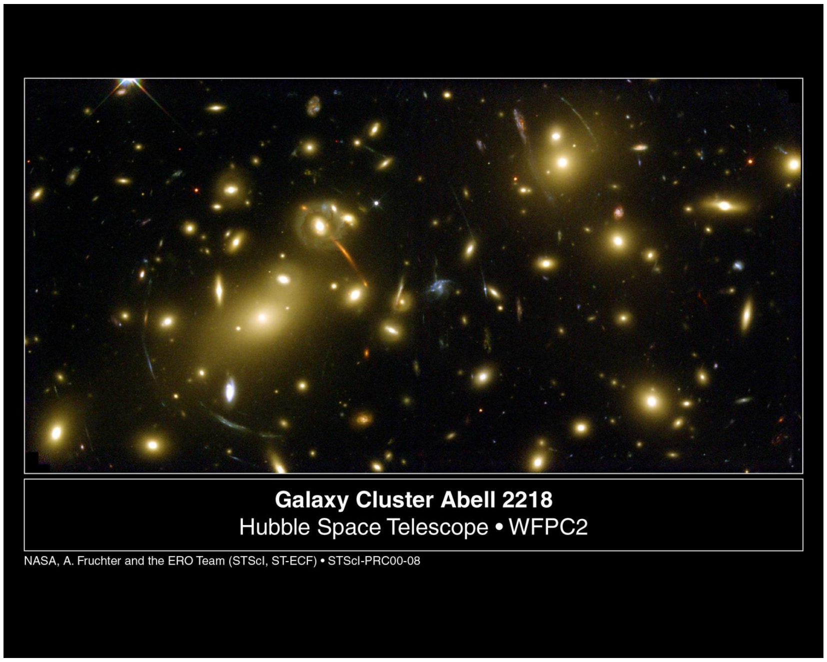


Figure 12.12 Unlike in the previous image, in this image the mass distribution is not symmetric about a single central galaxy. This is clear by the different arcs that are centered on different regions. In this cluster, called Abell 2218, the mass is much clumpier than it is in Abell 1689. Credit: NASA/Hubble Space Telescope

In addition to the magnification seen in point-source lenses, extended lenses create another effect called shear. The shear causes images to be stretched or distorted: it is a kind of astigmatism, similar to that found in poorly shaped glass lenses—or in the eye lenses of some people. The image of a background galaxy will not only appear larger than the galaxy itself, it will also be distorted. The effects of both magnification and shear are easily seen in Figures 12.11 and 12.12. Figure 12.13 gives a schematic rendering of how magnification and shear work when a gravitational lens is caused by an extended mass distribution. Both effects will usually be present in a gravitationally lensed image. Of course, the exact amount of magnification and shear depend upon the particular mass distribution causing the lens effect, as well as the geometry of the source-lens-observer system.

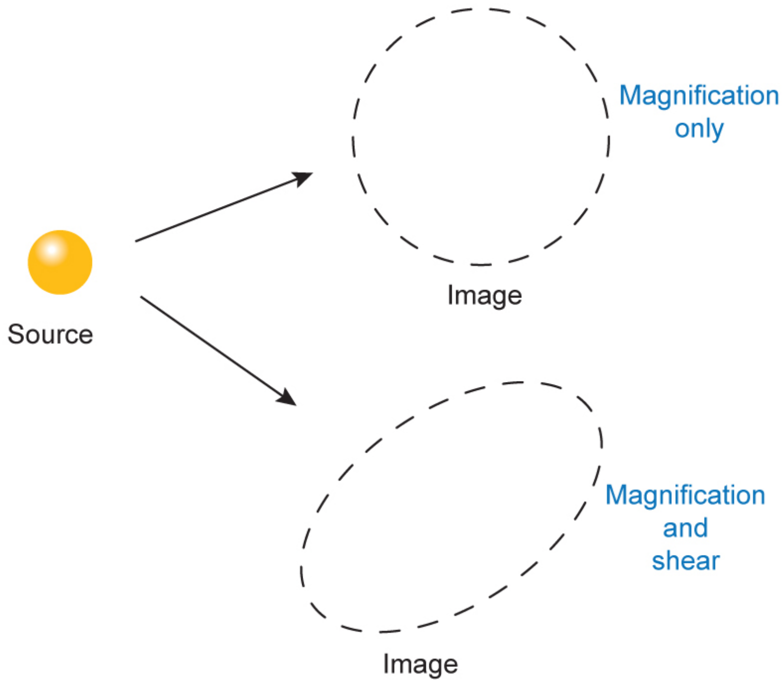


Figure 12.13 A circular source, as shown on the left, will be modified in two distinct ways by a gravitational lens with an extended mass distribution. At top right simple magnification is shown. The object does not change shape, but is enlarged by the lens. At the lower right the effect of shear is shown. The object is distorted such that its shape is modified. In general, gravitational lenses will produce both kinds of effects. Credit: NASA/SSU/Aurore Simonnet

To get a more realistic idea of how background sources are distorted by gravitational lenses, it is necessary to use a computer to simulate the bending of light rays. This is how astronomers study gravitational lens systems. Using computer models, the scientists are able to vary the amount of mass and its distribution, as well as the geometry of the lens. They can then compare what they see in the sky to the output of their simulation and draw conclusions about the nature of the lens.

The following activity provides an opportunity for you to examine a variety of images and to determine the type of lens that produced the gravitational image distortions.

### Different Types of Lenses

In this activity you will be presented with several gravitational lens images. Your job is to identify the type of lens that produced each image: spherical, elliptical, or clumpy. The source object in all cases is a galaxy.

- The images are laid out in a grid. Click on the tile for an image that you would like to classify in order to see a larger version of the image and decide what type of lens produced it.
- If you are correct, the tile will pop back into place and turn blue.
- If you are incorrect, you will be given a hint.
- Once the lens types for all of the images are properly identified, your task is complete.

**Play Activity**

Image credits for this activity: NASA/ESA/Hubble Space Telescope

There are certain sorts of lens geometry for which the magnification of the background image is particularly strong. The images tend to be larger, though generally more distorted, for these kinds of geometry. This happens when the source of light lies behind a caustic. This is a term from optics and describes places where parallel light rays are brought to a focus. For a well-behaved spherically symmetric lens, a caustic is simply the focus of the lens, but even when lenses are not perfectly formed (as with water waves or gravitational lenses), there are places where parallel rays of light will be collected. Figure 12.14 shows examples of caustics and how they are produced.

Figure 12.14 (Top) Caustics are places where parallel rays are directed by a lens. (Bottom) Caustics in a lens system composed of a glass of water or water in a pool. They appear as the bright areas next to the glass of water or at the bottom of the pool.Light passing through these points will be parallel after passing through the lens, so objects behind a caustic receive particularly strong magnification and distortion. Credit: NASA/SSU/Aurore Simonnet and Kevin McLin

## 12.3.2: Masses of Gravitational Lenses

When astronomers compare their models to observed lenses, they are able to determine many properties of the lens. In particular, they can deduce the amount of mass in the lens and its distribution. Scientists understood quite early that these analyses might provide a way to measure the mass of galaxies. And gravitational lenses provide a mass measurement that is totally independent of dynamical methods such as the rotation curves of galaxies or the motions of galaxies in a cluster. Because the two methods are distinct, the the lens masses are an excellent check on the dynamical method. If both give consistent values for the masses of systems, we will have added confidence that the masses obtained are correct.

However, the lens masses do have limitations, just as dynamically determined masses do. For instance, the mass distribution of the various lens components must be assumed. In complex lens systems there can be confusion between the mass distribution in individual galaxies and the effects of nearby galaxies, and it is not always possible to disentangle these using the image distribution alone. Furthermore, the lens analysis is only sensitive to mass within the Einstein radius of the lens, and that does not extend far enough out to probe the entire mass structure of a galaxy. The lens effect can also be subject to additional gravitational effects of unseen matter along the line of sight—in effect, this additional mass can mimic extra mass in the assumed lens itself.

In any event, when mass determinations are made using gravitational lenses they typically show the presence of much more mass than is seen directly via emission of electromagnetic radiation (light in any wavelength), just as the dynamical analyses do. In fact, lensing analysis often requires two or three times as much mass as is inferred using dynamics alone. The discrepancy is likely caused in large part by the uncertainties mentioned above.