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ENCYCLOPEDIA ARTICLE

Gravitational lens

A massive body producing distorted, magnified, or multiple images of more distant objects when its gravitational fields bend the paths of light rays. Lenses have been observed when the light from very distant quasars is affected by intervening galaxies and clusters of galaxies, producing several different images of the same quasar. A. Einstein predicted the occurrence of this phenomenon in 1936, but the discovery of real gravitational lenses did not occur until 1979. Gravitational lenses, in addition to being intrinsically interesting, can reveal the intrinsic properties of galaxies, active galaxies, and quasars, and provide information on the universe and its contents, including dark matter.

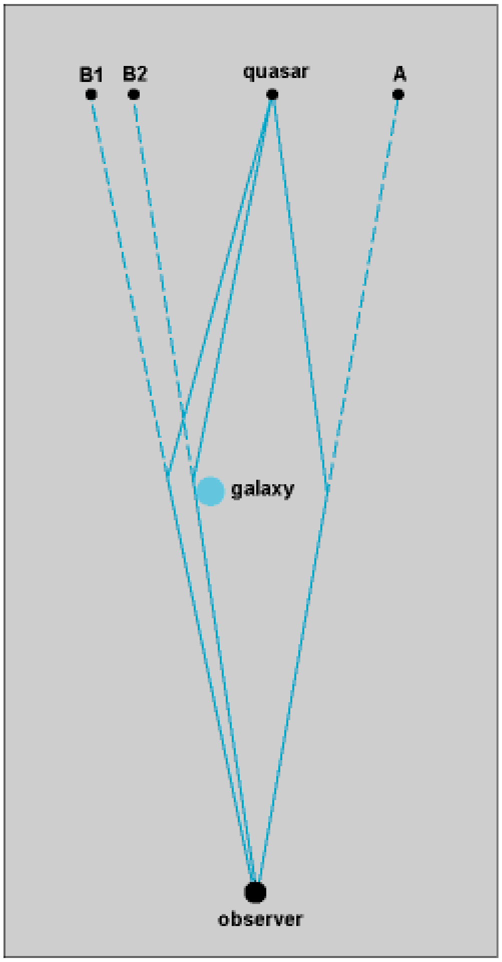
Action of gravity

The lens phenomenon exists because gravity bends the paths of light rays, which is predicted by Einstein's general theory of relativity. Since photons, the carriers of light energy, have no mass, Newton's theory of gravity indicates that light would always travel in a straight line even if there were heavy, massive objects between the source and the observer. (Even if photons are given mass in Newton's theory, the predicted bending of light is different from the result in general relativity.) But in general relativity, gravity acts by producing curvature in space-time, and the paths of all objects, whether or not they have mass, are also curved if they pass near a massive body. See also: Gravitation; Relativity

Numerous eclipse observations have confirmed Einstein's prediction with modest accuracies of 20–30%. Radio astronomers have measured changes in the positions of quasars that occur when the Sun passes near them in the sky. The precision of these experiments, which fit Einstein's predictions, is now at the level of tenths of a percent.

A massive object acts as a gravitational lens when light rays from a distant quasar are bent around or through it and are focused to form an image, which can be seen or photographed by an astronomer on Earth (**Fig. 1**).

Schematic illustration of a gravitational lens. The angles are exaggerated for clarity. Here, the lens action produces three images of a quasar (A, B1, and B2), since light from the image can travel along three different curved paths and still reach the observer.



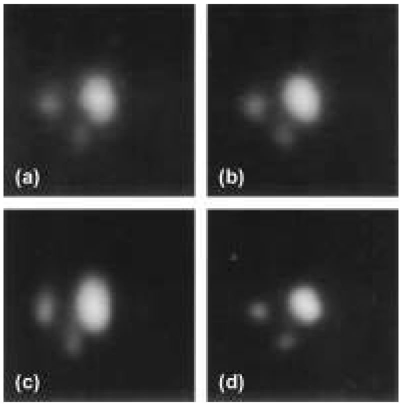
Sometimes a lens can amplify the total intensity of light in a quasar image, making it considerably brighter than the quasar would appear to be in the absence of a lens. If the galaxy and quasar are sufficiently well aligned, several images of the same quasar will appear, since light can travel on many different paths and still arrive at the detecting telescope. In some cases the lensed image is part of a ring. It has been shown that if there are multiple images of the same quasar, there must be an odd number of them, as long as the galaxy is big enough so that it does not act as a point mass.

Discovery of lenses

Astronomers treated gravitational lenses as curiosities for a long period of time. Space is so empty that the probability of two stars being aligned accurately enough is extremely small. But the discovery of quasars, hyperactive galaxies which are bright enough to be visible even though they are nearly 10^{10} light-years (1 light-year is equal to 5.88×10^{12} mi or 9.46×10^{12} km) away, made it possible to probe a much larger volume of space. Now, there was a reasonable chance that a galaxy might lie in the path of light traveling from a quasar to the Earth. See also: Quasar

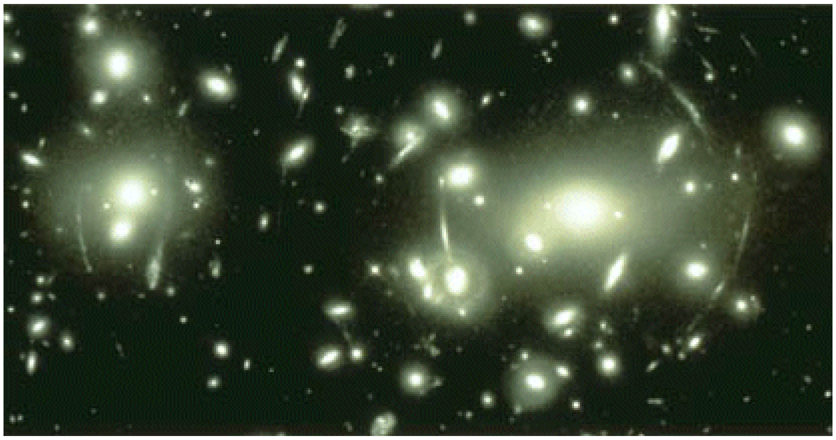
A survey of faint blue objects in the northern sky by Richard Green and Maarten Schmidt, completed in 1977, was one of the keys to establishing gravitational lenses as actual (as opposed to hypothetical) astrophysical objects. This Palomar-Green survey isolated several pairs of quasars, where two very similar faint blue objects were very close to each other in the sky. Subsequent investigation demonstrated that these two objects were not only very similar; they were two distinct images of the same object that were being produced when light from the object passed around a galaxy that was between the quasar and the Earth. In some cases, there were three images; **Fig. 2** shows one of the early multiple quasars, PG1115 + 08. (PG designates the Palomar-Green survey, and the numbers provide an approximate position in the sky in terms of the astronomical coordinates of right ascension and declination.)

Images of the triple quasar PG 1115 + 08. (*a*) Blue filter. (*b*) *V* band (yellow) filter. (*c*) Unfiltered image. (*d*) Red filter. (*From E. K. Hege et al*., *Morphology of the triple QSO PG1115 + 08*, *Nature*, *287*:*416–417*, *1980*)



More striking are some ringlike arcs produced when the distant object, the lensing galaxy or galaxy cluster, and the observer are exactly in a straight line. **Figure 3** is a picture, taken with the Hubble Space Telescope, of one of the most impressive arcs. When light passes through the cluster, it is bent. The distant object could be either a galaxy or a quasar, but it is definitely much farther away than the cluster. The cluster acts like a little telescope of its own, focusing the light from the distant object toward the Earth and making it brighter than it otherwise would be. See also: Satellite (astronomy)

Image of the galaxy cluster Abell 2218 obtained from the Hubble Space Telescope. The ring of light is an illusion, light from a very distant object that is bent by the gravity from the galaxy cluster. (*NASA*)



Implications

The discovery of gravitational lenses affects astronomers' understanding of the universe on the very largest scales. The very existence of this phenomenon indicates that nearly a dozen quasars—the ones that are being lensed—are more distant than the galaxies that are focusing their light. When quasars were first discovered, some astrophysicists argued that their redshifts were produced by exotic new physics and the quasars were just beyond the boundary of the Milky Way Galaxy. This controversy has largely subsided but has not been completely resolved. The lens phenomenon shows that at least some quasars are billions of light-years away, well beyond the edge of the Milky Way. If some quasars are billions of light-years away and others look like them, it is reasonable to conclude that all quasars are billions of light-years away at the edge of the observable universe.

Gravitational lenses can be used to determine the distance scale of the universe. Most quasars change the amount of light that they produce. In the case of a multiply imaged quasar like PG 1115 + 080 (Fig. 2), observers on Earth could see that change occur at different times because light travels on different paths to get here. The image where light travels on a more direct path would brighten first, and the one taking a more roundabout route would brighten later. The differences in the two path lengths can be used to deduce the distance to the quasar and the lensing object. Astronomers can then measure the redshifts of these distant objects and use the lens as another way to determine how fast the universe is expanding.

This seemingly easy idea is hard to implement in practice. Only one of 500 quasars is lined up in exactly the right way, and the mass distribution in the lensing object must be fully understood in order to interpret the data correctly. Sharp infrared pictures from the Hubble Space Telescope severely constrained possible models of the lens, making the interpretation much more secure. The data indicate a Hubble constant of 70 kilometers per second per megaparsec (the conventional units for measuring the Hubble constant), meaning that, if the universe has a very low density, its age is 14 billion years. See also: Cosmology

Dark matter

Gravitational lenses also enable the discovery of invisible objects. The speed with which stars move in galaxies and galaxies move in galaxy clusters indicates that many galaxies may be surrounded by massive dark halos. Since the matter that composes these halos cannot be seen, the name “dark matter” has been used to describe it. The dark matter could be brown dwarfs (objects not massive enough to be stars), dead stars, Jupiter-sized objects, or subnuclear particles. The more massive forms of dark matter are termed MACHOs (massive compact halo objects). See also: Brown dwarf

If a MACHO passed directly between a distant star and the Earth, the light from the star could be temporarily brightened as the MACHO focused the starlight toward the Earth. Precise calculations of this event indicate that the brightening should last about a week. Several teams of astronomers have made repeated observations of a nearby galaxy, the Large Magellanic Cloud, in search of this phenomenon, and seven such events have been detected. These events indicate that MACHOs, which are probably low-mass white dwarf stars, make up a sizable fraction of the mass of the halo of the Milky Way Galaxy, probably at least 20% of the dark matter and possibly as much as 100%. See also: Magellanic Clouds; Milky Way Galaxy; Hubble constant

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Additional Readings

- Gallery of Gravitational Images
- Gravitational Lens Data Base
- Max-Planck-Institut für Astrophysik (MPA), Gravitational Lensing Group
- Gravitational Lensing: Bibliography and Database

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