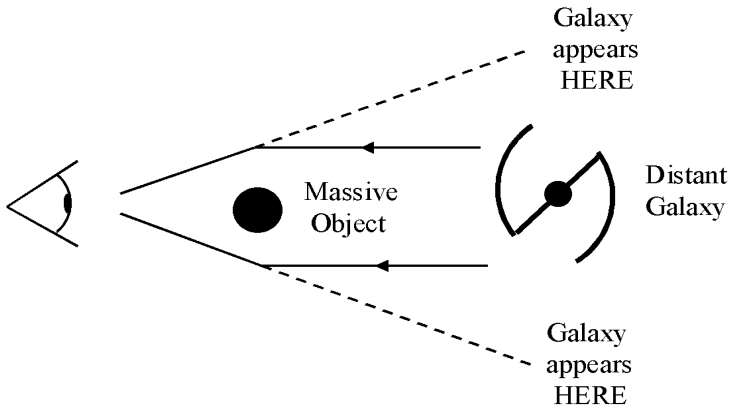
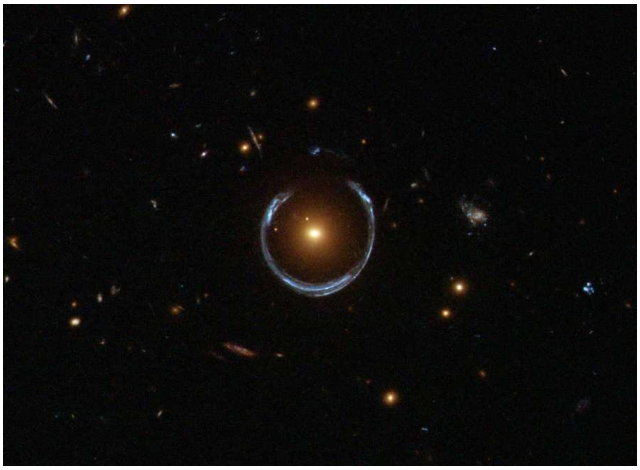
3.3 The Consequences of Einstein's Theory

Note. Since we postulate that gravity is a curvature of spacetime and that photons follow geodesics in spacetime, we find that "gravity bends light" (precisely, its the spacetime which is bent). The effect was experimentally verified in the famous 1919 eclipse expedition of Arthur Eddington. During a total eclipse of the Sun, the position of a star very near the Sun's limb was measured. The star's position was found to be shifted by an amount predicted by the general theory. See Figure III-4 on page 183. This experiment played a big role in making Einstein the "science genius" and public figure that he was to become in the 20's, 30's and 40's. This experiment has been reproduced a number of times using radio sources. A more contemporary example which is also a consequence of this "bending of light" is *gravitational lensing*. If a very distant galaxy is precisely along our line of site with a massive foreground object, then we will see multiple images of the background galaxy as the foreground object "focuses" the light rays. In some situations, the image appears curved and is a segment of the so called *Einstein ring*.



Note. A very nice example of an Einstein ring is the "Horseshoe Einstein Ring." Known as LRG 3-757, this was discovered in 2007 in data from the Sloan Digital Sky Survey. This is a Hubble Space Telescope image and was NASA's "Astronomy Picture of the Day" on December 21, 2011. See `apod.nasa.gov/apod/ap111221.html`.

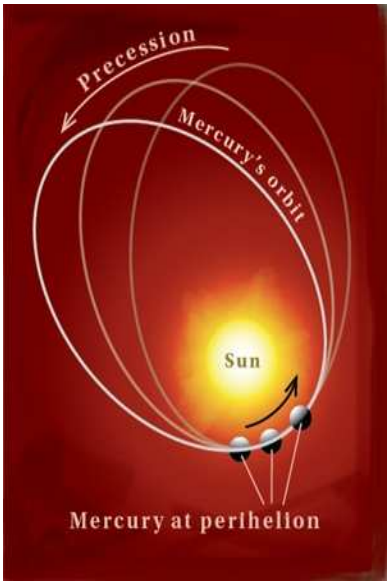


Another example gravitational lensing is the following (also a Hubble image):

"Astronomers are certain the blue-shaped objects are copies of the same galaxy because the shapes are similar. The cluster is 5 billion light-years away in the constellation Pisces, and the blue-shaped galaxy is about 2 times farther away." See `hyperphysics.phy-astr.gsu.edu/hbase/astro/quasar.html`.

Note. Einstein's original 1916 paper (see *The Principle of Relativity: A Collection of Original Memoirs on the Special and General Theory of Relativity* by H. A. Lorentz, A. Einstein, H. Minkowski, and H. Weyl, Dover Publications (1952), pages 109–164, includes a brief description of the bending of light around an object of a given mass. He even predicts the deflection of a ray of light by an amount of $1.7''$ at the limb of the sun; this is the prediction that Eddington confirmed in 1919. See pages 162 and 163 of the Dover book.

Note. A second example of experimental evidence for the general theory is the precession of the orbit of Mercury. Mercury orbits the Sun in an elliptical orbit ($e \approx .2$) and therefore experiences different accelerations due to the Sun. This results in a precession (or shifting) of the perihelion (point of the orbit furthest from the Sun) over consecutive orbits (see the figure below).



From `http://discovermagazine.com/2015/april/12-putting-relativity-to-the-test`

The observed precession is $43.11 \pm 0.45''$ per century and general relativity predicts a precession of $43.03''$ per century (see the table in Section 3.9 or Table III-2 on page 230 of the textbook). See pages 163 and 164 of the Dover book for Einstein's explanation of this in his 1916 paper. The closing paragraph of this famous paper is: "Calculation gives for the planet Mercury a rotation of the orbit of $43''$ per century, corresponding exactly to astronomical observation (Leverrier); for the astronomers have discovered in the motion of the perihelion of this planet, after allowing for disturbances by other planets, an inexplicable remainder of this magnitude."

Note. Urbain Le Verrier (1811–1877) reported the precession of Mercury's orbit in 1859 in "Lettre de M. Le Verrier à M. Faye sur la théorie de Mercure et sur le mouvement du périhélie de cette planète," *Comptes rendus hebdomadaires des séances de l'Académie des sciences* (Paris), **49** (1859), 379-383. A copy of the original work is online at `https://archive.org/stream/comptesrendusheb49acad#page/378/mode/2up`. Le Verrier proposes that an unknown planet inside the orbit of Mercury might be generating the precession. These historical comments about Le Verrier are based on the *Wikipedia* article on Le Verrier.

Note. Another prediction is the *gravitational redshift* of a photon in a strong gravitational field. We'll explore this in Sections 3.7 and 3.8. On page 162 of the Dover book containing Einstein's 1916 paper he says: "Thus the clock goes more slowly if set up in the neighborhood of ponderable masses. From this it follows that the spectral lines of light reaching us from the surface of the large stars must appear displaced towards the red end of the spectrum." Good empirical evidence for gravitational redshift was not in place in 1916.

Revised: 7/4/2016