12.1: What Are Gravitational Lenses?

Learning Objectives

- You will understand that gravity can bend the path of light.
- You will understand that this bending of light depends on the mass of the source of the gravity.
- You will understand that objects other than the Sun can act as lenses and that many instances of gravitational lensing have been seen.

What Do You Think: What is a Lens?

You are probably familiar with the glass lenses used to correct vision and construct instruments like cameras, microscopes and telescopes. These lenses use the fact that light travels more slowly through glass than through air, thereby causing the light to alter its direction of travel when passing from one substance to the other. By carefully shaping the glass/air interface, it is possible to bring all the light passing through the lens to a single point called the focus. To learn more about how optical lenses bend and focus light, see Going Further 12.1: Optical Lenses.

Gravity can also alter the direction that light travels. The effect is somewhat analogous to the way glass lenses work. Gravity, as a result, can sometimes act as a lens, focusing the light from a source. An optician would not consider the gravitational lenses we will study in this chapter to have very high quality; they have many imperfections that cause distortions of various kinds. Nonetheless, gravitational lenses provide astrophysicists with a powerful tool to probe the Universe.

GOING FURTHER 12.1: OPTICAL LENSES

Gravity bends space and time. Light rays follow this curvature and thus have their directions distorted by gravity. We can calculate the angle of deflection *(α)* of a light ray passing by a mass *(M)*. If we include both the space and time curvature pieces, the deflection angle is:

$$\alpha = \frac{4GM}{bc^2} = \left(\frac{4G}{c^2}\right)\left(\frac{M}{b}\right)$$

G and *c* have their usual values of 6.67×10^{-11} Nm^2/kg^2 and 3×10^8 m/s, respectively. The parameter b is called the impact parameter. It is the closest approach of the light to the massive object.

The expression has been written in two ways to make it more clear which parts are constant (the left hand bracket containing only constant terms) and which can vary. Only the mass and impact parameter can vary from one lens to another. The other terms are all constant.

The geometry of the deflection is shown in Figure 12.1.

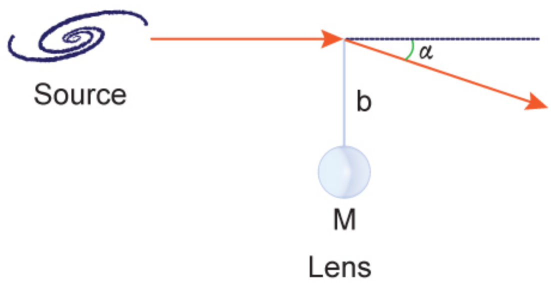

Figure 12.1 Light rays from a source are bent by the gravity of mass *M* (the gravitational lens). The angle of deflection is *α* and the distance of closest approach is *b*. Here we have made the simplification that a light ray bends only at the midpoint of the lens, whereas it actually follows the continuous (spherical) curvature of spacetime around the lens. Credit: NASA/SSU/Aurore Simonnet

For starlight passing by the Sun, the bending was only appreciable for light rays passing very close to the surface of the Sun. For light passing farther away the deflection became too small to measure. We can see that the expression for the deflection angle depends on the distance from the lens, and that the deflection becomes smaller as the impact parameter (b) becomes larger. But what if the Sun had a larger mass? Would the bending of starlight become noticeable at larger distances for a more massive object?

Again, looking at the expression for the deflection angle, if the mass of the lens is bigger, the deflection angle will be bigger, too. So the effect will be more noticeable if the lens has a bigger mass, regardless of how close the light passes to the object. Whether or not the deflection is noticeable just depends on the size of α, which itself depends only on the ratio of the mass to the impact parameter - the constant term is the same for any lens. As long as the mass and impact parameter combine such that the deflection angle is big enough, the lensing effect will be visible.

Gravitational Lensing by Objects Other Than the Sun

In this activity, we will compute the angle of deflection for light passing by objects other than the Sun. If we include both the space and time components of curvature, then light going just past the Sun is bent at an angle of about 2 arcseconds.

Worked Examples:

1. Calculate the angle α in radians for light skimming just past the outer edge of a white dwarf. Use a mass of 1.4 solar masses and a radius of 6.4×10^6 m for the white dwarf.

- Given: M = 1.4 solar masses = $1.4 \times 2 \times 10^{20}\ \mathrm{kg} = 2.8 \times 10^{30}\ \mathrm{kg}\ b = 6.4 \times 10^6\ \mathrm{m}$
- Find: deflection angle α
- Concept: $\alpha = \dfrac{4GM}{bc^2}$
- Solution:

$$\alpha = \frac{(4)(6.67 \times 10^{-11}\ \mathrm{N\,m^2\,kg^{-2}})(2.8 \times 10^{30}\ \mathrm{kg})}{(6.4 \times 10^6\ \mathrm{m})(3 \times 10^8\ \mathrm{m\,s^{-1}})^2} = 1.3 \times 10^{-3}\ \mathrm{radians}$$

2. Now convert this angle to arcseconds.

Use the conversion factor $1\ \mathrm{radian} = 2.06 \times 10^5\ \mathrm{arcsec}$.

$$1.3 \times 10^{-3}\ \cancel{\mathrm{radian}} \times (2.06 \times 10^5\ \mathrm{arcsec} / \cancel{\mathrm{radian}}) = 267\ \mathrm{arcsec}$$

3. Now compare to the deflection of light by the Sun.

The deflection by the Sun is about 2 arcsec, so this angle is 267/2 = 133 times greater.

Questions:

1.

2.

3.