Gravitational lenses

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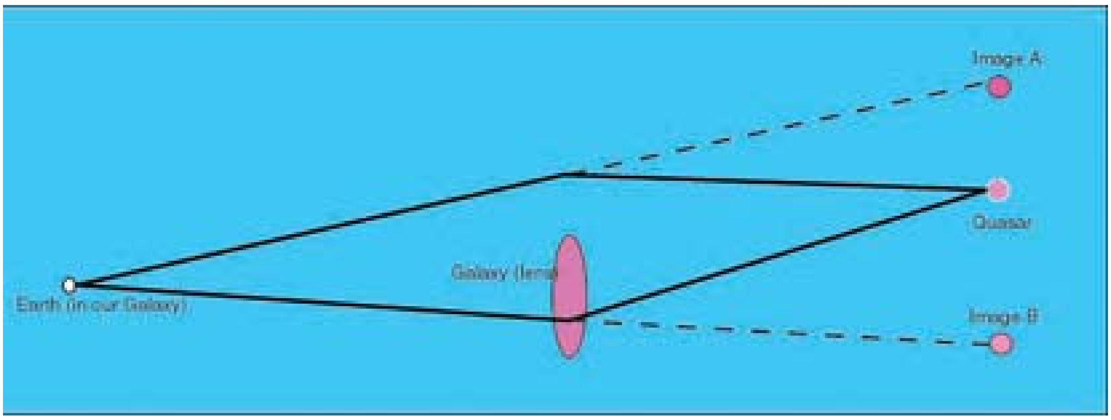
How rapidly (or slowly) does the Universe expand?
How old is the Universe?
How much matter does the Universe contain?
What are the mysterious Quasars?

These were some of the questions that a group of astrophysicists were trying to answer during their stay at the Centre for Advanced Study in 1997 to 1998. The group consisted of people from Denmark, Estonia, the USA and of course Norway. We all had a marvellous year and the friendly and efficient staff (Marit and Unn) made life easy for us.

In his General Theory of Relativity Albert Einstein showed how light would be deflected by a gravitational field. The effect of bending light rays by the gravitational field of the sun was measured during a solar eclipse in 1919, and in fact this was what made Einstein world famous. He also investigated the possibility of lensing effects from the gravitational field of a star bending the light from another star far behind. He concluded that such lensing effects (focusing, magnification and splitting up in two or more images) were hardly possible to observe.

Many years later, when the quasars were discovered, Sjur Refsdal was able to conclude that not only should lensing effects be possible to observe, but they could even be put to practical use. They could, among other things, be used to determine the mass of the lensing object, distances in the Universe, the rate of expansion of the Universe and the age of the Universe.

Another 15 years elapsed before the first gravitational lens system was serendipitously discovered in 1979. A team of British and American astronomers found an unusual "double quasar". The two quasars had almost identical spectra, showing that they were likely to be two images of the same quasar. After some time the "lens" was also discovered. The astronomers found a galaxy, nearer to us, that lay between the two images of the quasar, just in the position where the lensing galaxy should lie.



Two images of a single quasar may be observed when the light rays from the quasar are being bent by the gravitational field of a galaxy. The deflection (and therefore also the angle between the images) are strongly exaggerated. In reality the angle is of the order of arcseconds.

Since then many different types of lens systems have been discovered; many where a galaxy acts as a lens and some where the lens is a whole cluster of galaxies. Magnification and splitting of the source into two, three or even four images is quite common. Lens effects have also been observed where the lens is a single star or another small compact object.

The best observed lens system is by far the first observed case, the so-called Double Quasar. Our group had access to a quite unique series of observations of this system, so it was natural to use these data to make comparisons with our theoretical predictions.

Many quasars vary in brightness, and the Double Quasar is no exception. When we look at the figure illustrating a typical lens system giving two images of one source, we immediately see that the light paths are slightly different. Hence we should not expect to see the two images change their brightness at the same time. A change in the luminosity of the quasar should be seen first in one image and some time later in the other. This time delay can be measured and is crucial for our determination of the distance to the lens. By comparing the two observed lightcurves (the change in brightness with time) for the two images, we were able to determine this time delay. This, however, was not an easy task. Due to different types of interference in the data, advanced statistical methods had to be used. The difference in light travel time was found to be only about 14 months, in good agreement with other investigations.

By means of this time delay one is able to determine the light travel time. The time the light has taken to reach us turns out to be directly proportional to the time delay. The light forming the two images has been under way for about 10 billion years. That in turn gives the distance to the lens. This elegant way of determining a distance in the Universe was known more than 15 years before the first gravitational lens was observed; it is called the Refsdal method.

We were now in a position to pin down the rate of expansion of the Universe, the Hubble parameter, H. Since the redshift of the lens is known, we practically know the expansion velocity, v, at the distance, d, where we find the lens. The famous Hubble's law tells us that the expansion velocity is directly proportional to the distance; $v = Hd$, with the constant of proportionality, H, telling us how much the velocity increases with distance. The result was not very surprising; we found that $H = 20$ km/sec per million light years, a value lying snugly in the middle of earlier estimates.

This result together with a fairly good idea of which cosmological model is best for describing our Universe, gives us a good estimate of the age of the Universe. We found it to be about 15 billion years old. This value is also in good agreement with other estimates using quite different methods.

In systems where the gravitational lens is a whole galaxy, as in the case of the Double Quasar, individual stars and other compact objects (planets or black holes) in the galaxy may act as small lenses. Due to transversal motion we may then observe variations in the light source on time scales of years. This is called “microlensing” to contrast it with “macrolensing” by the smoothed-out gravitational field of the entire galaxy. In our data there was one such case of a microlensing effect, and we found a method to use this effect to constrain both the mass of the microlenses and the size of the quasar. Two quite interesting results followed from our analysis.

1) The observed microlensing effect could easily be explained by ordinary stars, but in special cases even planets (!) could give similar effects.

2) The size of the quasar is probably of the order of a light day!

This small size confirms the most popular hypothesis for explaining the quasar phenomenon: A giant black hole with a mass of about a billion solar masses is lurking in the center of a galaxy and is swallowing the material (in the form of stars, gas and dust) that comes too close.

GLOSSARY:

Black holes: A region of space where the gravitational forces dominate over all other forces. It is formed when a mass undergoes a complete collapse.

Galaxy: Large systems of billions of stars (plus some gas and dust). Our Galaxy contains about 200 billion stars and has a diameter of about 100 thousand light years.

General Theory of Relativity: Einstein's famous theory of gravitation from 1916. It describes gravitation by means of geometry of space-time. All tests are in excellent agreement with the theory.

Quasar: Extremely energetic “Active Galactic Nuclei” in distant galaxies. It occurs where a giant black hole is swallowing surrounding matter.

Redshift (cosmological): The shift of spectral lines towards longer wavelengths observed in the spectra of distant objects. It is caused by the expansion of the Universe.