Light echoes from a Cepheid star yield its distance
Cepheids are variable stars, which follow a relation Period-Luminosity (P-L), allowing to determine their distance. To better calibrate this P-L relation, it is necessary to determine the distance of a sample of Cepheids by another method. Light echoes allow this calibration. There are echoes when the Cepheid is surrounded by a dust nebula: light is then scattered by dust, and returns towards the observer, with a delay in comparison with the light propagated directly. Knowledge of the geometry of the dust in the nebula allows to derive the distance to the star. An international team of researchers, led by an astronomer of Paris Observatory, has determined the distance of RS Puppis using its light echoes with a precision of 4%.

The star of the southern hemisphere RS Puppis is a Cepheid whose brightness varies regularly with a period of 41.5 days and an amplitude of a factor three in the visible. Cepheids are pulsating stars whose size and brightness varies with a period of a few days to several weeks. The long-period Cepheids as RS Pup stars are particularly important in astronomy because they allow us to estimate the distances to distant galaxies, and thus map the universe. For this, we use a special relationship between the period of variation of the Cepheid and its intrinsic brightness: the longer the period, the brighter the star. This is the period-luminosity relation (P-L). The measurement of the period is simple to perform, as well as that of the average apparent brightness of the star (as seen from the Earth). With the PL relation, one can know the distance by comparing the absolute luminosity of the star to its apparent brightness as seen from the Earth (the apparent brightness decreases with the square of the distance).
The key point of this method is the accuracy with which we know the PL relation of Cepheids. To calibrate this empirical relationship, it is necessary to know the distance of a sample of Cepheids by another method. The measurement of the trigonometric parallax is not applicable here, because the distance of 6300 light years is too high for current instruments. But it will be measured by the GAIA satellite in the coming years.

RS Pup has the unique property among Cepheids to be surrounded by a large nebula of dust with a size of several light years, which diffuses the light from the central star (Figure 1). The variations of the star are reflected in the dust, creating one of the most spectacular examples of the phenomenon of light echoes.

Figure 1. Nébuleuse de poussière entourant la Céphéide RS Pup (crédit : NASA/ESA/Z. Levay/Hubble Heritage Team). Les échos de lumière sont visibles comme des anneaux bleutés pratiquement centrés sur l'étoile.
Due to the finite speed of light (300 000 km/s), the changing intensity of the light is reflected in the Cepheid Nebula with a delay which depends on the additional path between the star and the dust nodules of the nebula. Light coming directly from the star (without reflection on the dust) takes about 6300 years to reach us. The travel time of the reflected light is a little longer, due to the additional path between the star and dust. Typically, this additional travel time is of several days to several months in the case of RS Pup, given the fact that the dust is distributed on a radius of a few light years around the Cepheid.

Figure 2. Géométrie des échos de lumière autour de RS Pup.

As the brightness of the star varies with time, the phenomenon of light echoes manifests as light waves propagating in the nebula from the star. The light echoes have the same appearance as the circular ripples propagating on the surface of the water after the impact of a drop, but the geometry is in reality quite different. Figure 2 shows that the echoes appear at the intersection of a series of paraboloids of revolution representing the maximum light from the star with the dusty surface of the nebula. Unlike the waves at the surface of a liquid, the apparent propagation velocity of the light waves of the echoes in the nebula is not constant. It is infinite in theory on the star itself, and then decreases with the angular separation. Due to the spatial distribution of the dust, the apparent propagation rate remains greater than the speed of light up to a large distance from the Cepheid. This supra-luminic speed is not in
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contradiction with the theory of relativity because it is not a real propagation velocity in space, but simply an effect of geometric projection.

Knowing the geometry of the dust distribution in the nebula, it is possible through observation of the echoes to deduce the distance of the star. The distance of RS Pup is particularly important because it is a long-period Cepheid of the same type as those used to estimate extragalactic distances. The light echoes offer an original and independent method for measuring the distance with respect to more conventional methods applied to Cepheids.

A delicate point of distance measurement by light echoes is the determination of the three-dimensional structure of the nebula. It is indeed necessary to know it to model uniquely the echoes, and derive the distance. Figure 2 shows the ideal case of a planar distribution of the dust, but the actual distribution is more irregular and complex. In order to reconstruct the distribution, the light scattering angle by the dust must be estimated. This is possible by using the polarization of light scattered by the dust. This is what was done by observations from the Hubble telescope. A map of the polarized light from the southern part of the nebula is shown in Figure 3 The degree of polarization of the light is related to the angle at which the dust scatters light from the star. If this angle is small, the degree of polarization will be close to zero, and it is maximum (about 50%) for a right angle scatter. The map of the degree of polarization we obtained thus gives a scattering angle map, which allowed us to reconstruct the three-dimensional shape of the nebula.

The shape of the nebula, combined with the measurement of the phase of light echoes then gives us a measure of the distance of the star. We obtained 6230 light years with an uncertainty of 261 pc, an accuracy of 4%. This is currently the best accuracy on the geometric distance of a long period Cepheid. The distance of RS Pup was used to validate the current calibration of the Period-Luminosity relation of Cepheids.

Figure 3. Flux polarisé observé dans la nébuleuse de RS Pup. Les parties de la nébuleuse présentant une forte polarisation ont été sélectionnées pour la mesure de distance. Elles sont entourées en rouge sur l'image. La position de l'étoile est marquée par une croix.
Reference