RS Puppis: A Unique Cepheid Embedded in an Interstellar Dust Cloud

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The long-period Cepheid RS Pup illuminates its circumstellar dust cloud with a variable flux, and creates spectacular light echoes. Through photometric observations of this phenomenon with NTT/EMMI, and polarimetric imaging with VLT/FORS, we have derived the geometric distribution of the scattering dust and the total mass of the nebula. We conclude that the dust was not created by mass loss from the Cepheid, but is most probably a remnant of the interstellar material from which the Cepheid formed.

Light echoes: a stimulating geometrical puzzle

Cepheids are historically the most important class of variable stars, thanks to the relation between their pulsation period and absolute luminosity; that relation played a key role in the discovery of the expansion of the Universe. In particular, long-period Cepheids are so bright that they can be observed in very distant galaxies, and act as standard candles to measure their distances. With its 41.4-day pulsation period, RS Pup is one of the brightest known long-period Cepheids in the Galaxy. But this star also stands out as the only known example of the intimate association of a Cepheid with a dust cloud (Figure 1, left). The discoverer of the nebula of RS Pup, Bengt Westerlund (Westerlund, 1961), has already remarked that "the nebula may be large enough to permit the detection of possible variations in its intensity distribution due to the light variations of the star". The existence of this "light echo" phenomenon, created by the propagation of the luminosity variations of the star in the nebula, was subsequently confirmed by Havlen (1972).

The geometrical configuration of the light echo phenomenon is somewhat counter-intuitive, as its morphology depends both on the three-dimensional distribution of the scattering material, and the position of the observer (see, e.g., Sugerman [2003] for details). Figure 2 shows a schematic view of the propagation of the maximum light wavefronts emitted by RS Pup into space. The geometrical shape of these wavefronts is almost a paraboloid (rigorously, they are very elongated ellipsoids). Their intersection with a thin light-scattering dust layer produces "light rings", such as those visible in Figure 1 (right). For the nebula of RS Pup, the irregular distribution of the dust results in imperfectly circular rings.

Light echoes are particularly interesting as they may provide a means of measuring the geometrical distance to the central star. For a Cepheid like RS Pup, such an independent distance measurement is of great interest for the calibration of the Period–Luminosity relation. From imaging of the light echoes with the ESO Multi-Mode Instrument on the New Technology Telescope (NTT/EMMI), Kervella et al. (2008) derived its distance based on the assumption that the observed nebular features are located close to the plane of the sky. However, as argued by Bond & Sparks (2009), this simplifying assumption could lead to a significant bias on the determined distance. To derive the distance of RS Pup unambiguously using its light echoes, we therefore need first to determine the three-dimensional geometry of the dust nebula.

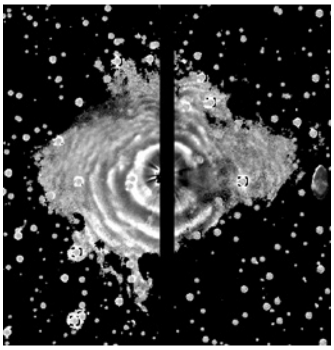

Figure 1. Left: Three-colour *BVR* composite image of the nebula of RS Pup obtained using the NTT/EMMI instrument. Upper: Ratio of two images obtained a few days apart, showing the light echoes (from Kervella et al., 2008).

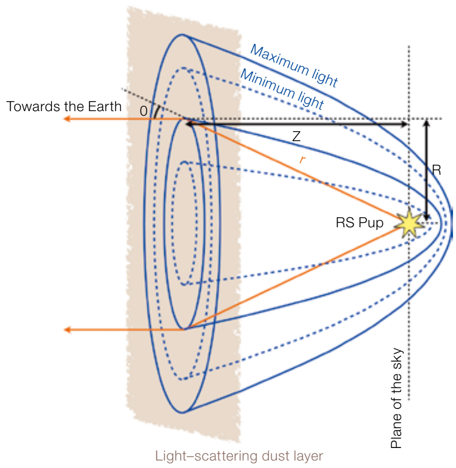

Figure 2. Geometry of the propagation of the maximum and minimum light wavefronts in space, for an observer located to the left of the figure.

The first piece of information on the dust geometry is provided by the high contrast of the light echoes in the nebula. The relative amplitude of the photometric variation on any part of the nebula is comparable to the variation of the central star itself. As shown in Figure 3, the amplitude of the luminosity variation of RS Pup is relatively large, particularly in the *B*-band (there is almost a factor of five between the minimum and maximum luminosity). The fact that this high amplitude is preserved in the scattered light indicates that the dust is confined in a geometrically thin veil, as a thick layer would result in the out-of-phase superposition of different wavefronts, and therefore the disappearance of the echoes.

To determine the spatial shape of this dust layer, we used the particular linear polarisation signature of the scattering of light by dust grains. The degree of linear polarisation ρ of the scattered light is linked to the scattering angle θ, i.e., the angle between the incident and emergent directions of the photon (see Figure 2). The maximum polarisation is ~ 50% for a scattering angle of $\theta = 90°$, i.e. for scattering material located in the plane of the sky, and a zero polarisation degree is obtained for forward or backward scattering (θ = 0 or 180°). We used the empirical calibration of the $\rho(\theta)$ relation obtained by Sparks et al. (2008) from the light echo of the cataclysmic variable star V838 Mon. This relation is very close to the theoretical scattering law for very small dust grains (Rayleigh scattering). From a measurement of ρ, we can therefore retrieve the scattering angle θ.

The projected angular separation *R* is directly measured in the images, and by combining *R* and θ, we can estimate the altitude of the scattering material $Z = R/\tan(\theta)$ above the plane of the sky (i.e. the imaginary plane orthogonal to the line of sight, located at the distance of RS Pup). It should be noted that backward scattering is much less efficient than forward scattering, and we therefore observe essentially the material located between RS Pup and us, while the dust located behind RS Pup will be very much fainter.

To measure θ for each point of the nebula, we took advantage of the polarimetric imaging mode of the FORS spectrograph

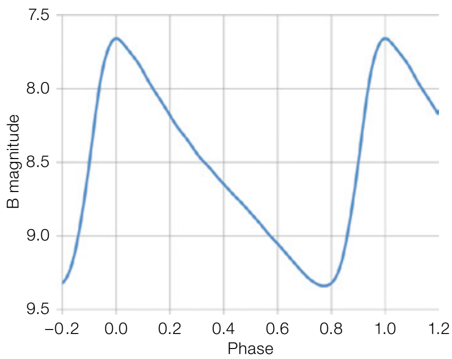

Figure 3. The light curve of RS Pup in the *B*-band (data from Berdnikov et al. [2009]).

on the Very Large Telescope (VLT/FORS; Kervella et al., 2012). The resulting polarimetric images allowed us to derive a map of the degree of linear polarisation over the nebula (Figure 4, upper right). The altitude *Z* of the dust layer relative to the plane of the sky is obtained in the same physical units as the projected distance *R*. As a consequence, to obtain the altitude in absolute linear units, we have to assume the distance of the star to be 1.8 ± 0.1 kpc (estimated from indirect techniques). The resulting altitude map is presented in Figure 4 (lower left).

The light-scattering material surrounding RS Pup appears to be spread over an irregular surface, with no well-defined central symmetry relative to the Cepheid. The visual shape of the nebula (Figure 4, upper left) appears more symmetric, due to the higher efficiency of forward

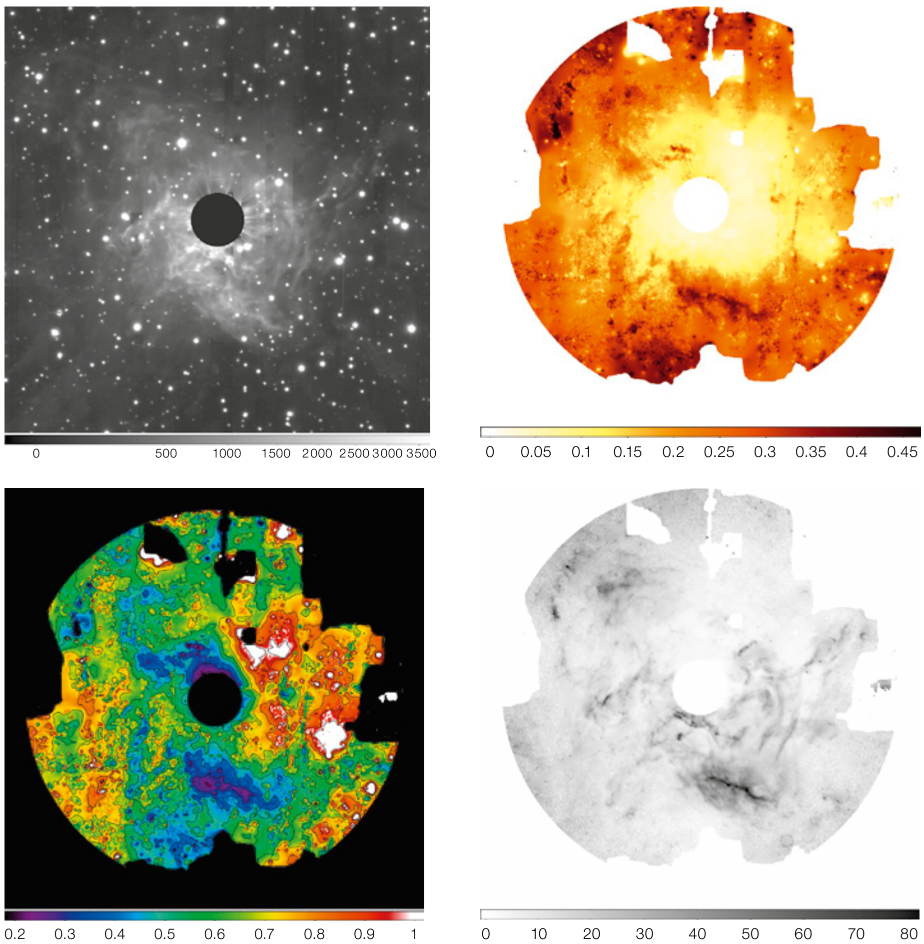

Figure 4. Upper left: FORS+EMMI combined intensity image of the nebula of RS Pup in the *V*-band (field of view 4 by 4 arcminutes). Upper right: Map of the degree of linear polarisation measured with FORS. Lower left: Altitude of the light-scattering dust layer in front of RS Pup, relative to the plane of the sky (in parsec). Lower right: Density of the scattering material (in units of 10^{54} H atoms per square arcsecond, i.e. the equivalent number of hydrogen nucleons in the scattering material). From Kervella et al. (2012).

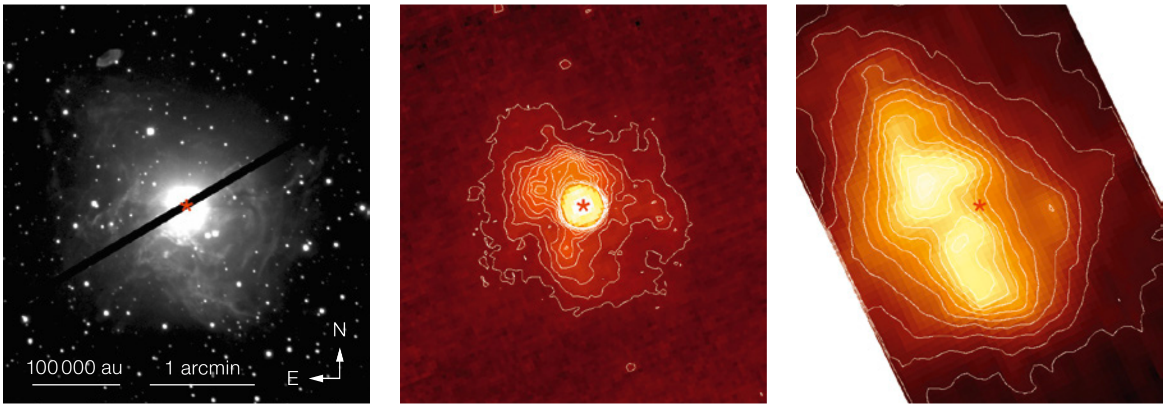

Figure 5. Images of the nebula surrounding RS Pup in the *V*-band (EMMI, left), and Spitzer infrared images at 24 µm (middle) and at 70 µm (right), on the same spatial scale. The position of the Cepheid is marked with a star symbol (from Kervella et al., 2009).

scattering that tends to emphasise the material located close to the line of sight. High degrees of linear polarisation (~ 50 %) are observed for several nebular knots, showing that their position is close to the plane of the sky (represented in blue in Figure 4, lower left).

Origin of the dust nebula

As we have determined the geometry of the dust layer, it is now possible to compute the physical distance r between each point in the nebula and the Cepheid ($r^2 = Z^2 + R^2$, Figure 2). Knowing r and the scattered light flux, we can deduce the local density of the scattering material at any location on the nebula. Figure 4 (lower right panel) shows the resulting density map.

Compared to Figure 4 (upper left), the highest densities do not generally correspond to the brightest parts of the nebula. This is easy to understand as the scattered light flux depends both on the scattering angle θ and the linear distance r between the star and the dust. A particularly prominent feature is the "ridge" structure visible south of RS Pup. This filamentary dust cloud is located close to the plane of the sky, with a slight inclination, as shown in Figure 4 (lower left).

From the density map, assuming standard interstellar dust properties, we estimate the total mass of the light-scattering dust to be 2.9 ± 0.9 $M_{\odot}$. This value should be regarded as a lower limit to the true mass of the nebula, as we sample only the material in front of RS Pup, while dust is likely to be present also behind the plane of the sky. In addition, we include in this figure only the material that is illuminated by RS Pup within 1.8 arcminutes from the star. FORS and EMMI long exposures show faint nebular extensions far beyond this region, at least up to a radius of 3 arcminutes. These distant parts are too faint to measure their degree of linear polarisation.

This determined mass corresponds only to the light-scattering dust, but does not include the gaseous component, that is transparent to light. The typical gas-to-dust mass ratio in the Galaxy is ~ 100. The total mass of the nebula, including the gas, is therefore approximately 300 solar masses. Such a high mass is clearly incompatible with the scenario that RS Pup created the nebula through mass loss (the mass of the Cepheid itself is estimated to be ~ 13 $M_{\odot}$). Most of the dust observed in scattered light therefore appears to be of interstellar origin. The higher density dusty environment in which RS Pup is presently located could either be the remnant of the molecular cloud from which the star formed, or unrelated interstellar material into which RS Pup is temporarily embedded, due to its motion in the Galaxy. The thin veil geometry of the dust layer is probably created by the radiation pressure from the extremely bright Cepheid (~ 17 000 $L_{\odot}$), that sweeps the interstellar dust away from the star.

Prospects

Thanks to our EMMI and FORS observations, we have established that RS Pup did not create the nebula in which it is currently embedded. This peculiar configuration provides a natural explanation to the scarcity of similar Cepheid–nebula associations, and also confirms that the presence of such nebulae is probably not a significant source of photometric bias for the calibration of the Cepheid Period–Luminosity relation. Our determination of the three-dimensional distribution of the dust will also allow us to use the phase of the light echoes to determine unambiguously the distance of RS Pup. This is a particularly important piece of information for this rare, long-period Cepheid, which is a typical example of the stars used to determine extragalactic distances.

As RS Pup illuminates the nebula, part of its radiation is absorbed by the dust, which warms up and emits radiation by itself. As the dust is still rather cold (~ 40–60 K; Barmby et al., 2011), this emission occurs in the infrared domain, but it is clearly observable in the Spitzer images presented in Figure 5. With observations of both the scattered light in the visible, and the thermal emission in the mid-infrared domain, together with the three-dimensional map of the dust distribution, RS Pup is a particularly promising test case for the study of interstellar dust properties.

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