RS Puppis: the light echoes calibrate standard candles for accurate distance measurements

Cepheids allow astronomers to measure vast distances across space. RS Puppis is an unusual cepheid embedded into an interstellar dust cloud illuminated by the variable light, enabling a phenomenon known as a light echo to be observed in details. Sparks (1994) showed that the polarization of a light echo can be used to measure its distance geometrically. This approach was used to determine the distance to RS Puppis with great accuracy, and hence calibrate the cosmic distance scale, based on the period-luminosity relation of classical Cepheid variables.

Cepheids are giants and supergiants which lie in the instability strip. Because they are intrinsically luminous, they can be seen to great distances. RS Puppis is a bright and easy to spot star for southern hemi-sphere observers. The star lies about 6,500 light-years away from Earth. It is over 10 times more massive and 200 times larger than our Sun. RS Pup periodically changes brightness over a six-week cycle (41.4 days), pretty long and comfor-table for visual observers. As RS Puppis expands and brightens, astronomers see some of the light after it is reflected from distant shells of dust and gas surrounding the star. Its average intrinsic brightness is 15,000 times greater than our Sun's luminosity. RS Pup remains one of the longest period Cepheids, in a class with stars like U Car (38.76 days) and SV Vul (45.01 days).

NASA's Hubble Space Telescope photo of the variable star RS Puppis and its surrounding cloud of gas and dust, accompanied by the light reflected from distant shells of dust. RS Pup is a Cepheid variable that brightens and dims as it expands and contracts.

Credit: NASA, ESA, and the Hubble Heritage Team (STScI/AURA)-Hubble/Europe Collaboration

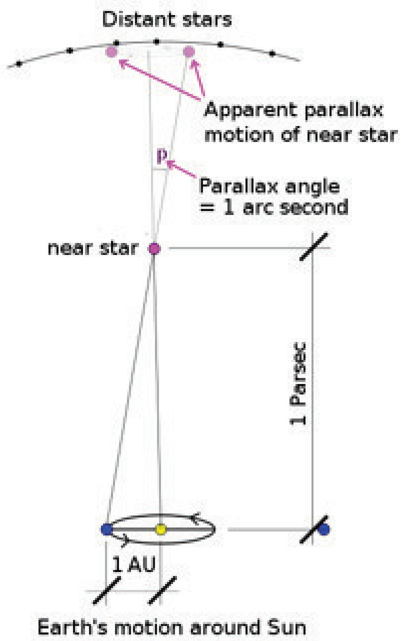
By observing RS Puppis light fluctuations and recording reflections of light pulses moving across the surrounding nebula, scientists were able to measure these faint light echoes and calculate the distance very accurately.

Because of their geometry, light echoes can produce an *illusion* of superluminal speeds. A good explanation of this effect is given in AAVSO's note called "*Visible Superluminal echoes*" available at http://www.aavso.org/vsots_gkper. Light reflections allowed to determine the distance to the Cepheid variable RS Puppis quite reliably (with a margin of error of only one percent).

The bodies of which the intrinsic luminosity is well known are referred to as "standard candles". Cepheid variable stars were the key instrument in Edwin Hubble's 1923 conclusion that M31 is an external galaxy.

Cepheids are good standard candles as their luminosity is quite high and can be computed from the Period-Luminosity Relation, first discovered in 1912 by *Henrietta Leavitt*. The most luminous Cepheids can be ~100K times more luminous than the Sun, which allows to use them as standard candles for distances up to 30-50 Mpc.

The only directly measurable distances in astronomy are those made by trigonometric parallax, which is useful for distances out to about 50 parsec for ground-based optical and a few hundred parsecs for space-based observa-tions. The accuracy is limited by the smallness of the motions (see the picture on the right). There are no Cepheids known this close to the Sun.



Trigonometric parallax can be measured only for nearby stars. Image credit: Chris Martin

The first successful measurement of the distance to a star using trigono-metric parallax method was carried out by the German astronomer Friedrich Bessel in 1838, when he determined that 61 Cygni is 10.4 light-years away. More accurate recent measurements give a distance of 11.4 ly.

The nebula around RS Pup was discovered in 1961 by Swedish astronomer

Bengt Westerlund, who later became ESO Director in Chile (1970-74). In 1972, Robert Havlen published the first study of the nebula. Kervella et al. (2008) published a paper describing a method of distance calculation to the nebula by its geometric parameters, but later it was invalidated by Bond & Sparks (2009). In 2010, Hubble observed the star and its environment over a period of five weeks, capturing snapshots at different stages in its cycle, providing a basis for a more reliable result.

V838 Monocerotis

Another notable example of a star with a dusty nebula around and spectacular light echoes is V838 Mon. It is a red variable star in the constellation Monoceros about 20,000 light years from the Sun.

Left: These images show the evolution of the light echo around the star V838 in the constellation of Monoceros. They were taken by the Hubble Advanced Camera for Surveys in November 2005 (left) and again in September 2006 (right). The numerous whorls and eddies in the interstellar dust are particularly noticeable. Possibly they have been produced by the effects of magnetic fields in the space between the stars.

Credit: NASA, ESA and H. Bond (STScI)

Galactic light echoes are extremely rare. Before we can see echoes, there must have been a massive star explosion in the region. This remarkable event took place on January 6, 2002, one that had never been observed before, when previously unknown star suddenly brightened, just like a nova (Brown, 2002). But instead of a long dimming phase, it became brighter two months later. The third burst in April was even more powerful.

Early in the outburst, in mid-February 2002, a light echo surrounding V838 Mon was discovered by Henden et al. (2002). This allowed the distance to V838 Mon to be estimated from the evolution of the light echo. The cause of the eruption of V838 Mon and the nature of its progenitor are still unclear (Loon et al., 2004).

Series of images taken by the *Hubble Space Telescope* (above) did not reveal matter being blown away from an exploding object. What caused several cycles of brightening were light echoes illuminating an outer dust cloud. Two images above were taken by the HST in November 2005 and September 2006, showing no spherical shell around the star, but a quite irregular dust cloud highlighted in the vicinity of the central object. Unlike a classical nova, V838 Mon became progressively redder, eventually becoming the coolest known luminous star (Bond et al., 2003).

Initial estimates of the distance to V838 Mon done in (Munari et al., 2002) gave values of 0.6-0.8 kpc. These results were however based on a wrong interpretation of the observed expansion of the light echo. From a more realistic study of the echo structure (Bond et al., 2003) concluded that the distance is at least 6 kpc (Tylenda, 2005).

Hunting light echoes

The best places to search for light echoes are in the vicinity of our galaxy's historical supernovae. Particularly, blasts recorded in *1006* in Lupus, *1054* in Taurus (the remnant of which is known as the Crab Nebula), *1181* in Cassiopeia, *1572* in Cassiopeia ("Tycho's star"), *1604* in Ophiuchus ("Kepler's star"), and perhaps the late 17th century in Cassiopeia, the remnant of which is Cassiopeia A.

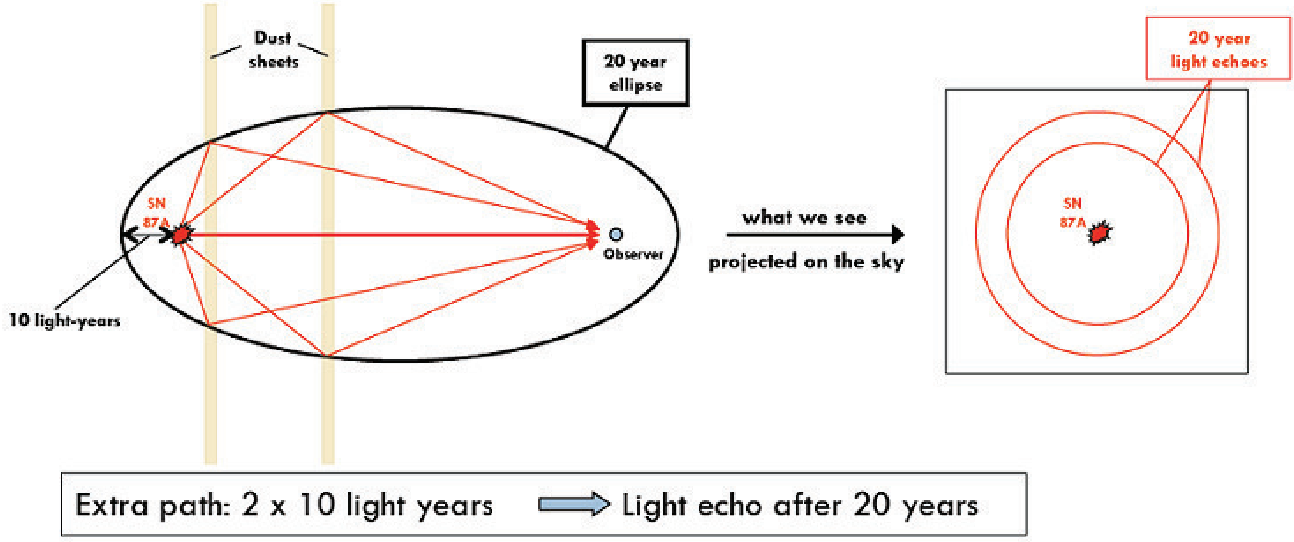
Right: Finder chart for light echoes around Supernova 1181, SN 1572 , and the 17th-century blast produced remnant Cas A. Credit: S&T June 2008 - Casey Reed / Source: Douglas L. Welch

More details on light echo observing targets can be read in the article "*How to Hunt for Supernova Fossils in the Milky Way*", written by Douglas L. Welch (S&T, June 2008) from McMaster University, Canada.

Basic geometry behind a light echo

While a flash from an exploding star travels out in all directions, it will still take years before it reaches the nearest dust cloud, heating it up. The cloud, which was too cold to detect directly before, begins to emit in infrared light. This infrared echo signal travels towards an observer, and due to a longer way it lags behind the original flash, which means it will arrive later for the observer. Though the second dust cloud is more distant from the star, the light will travel the same overall distance on its way to the observer, because of the geometric properties of an ellipse (as illustrated in the figure below). This means that light from both clouds will reach the Earth at the same time (see image below), resulting in two echoes simultaneously. A phenomenon known as *Visible Superluminal echoes.*

More at: http://www.spitzer.caltech.edu/images/2662-ssc2005-14d-Illustration-of-a-Light-Echo



Basic geometry behind a light echo: ellipsoids trace out surfaces of constant arrival time, causing an observer to see distant dust regions being highlighted by the exploded star as concentrated circles projected on the sky. Image credit: Armin Rest (Harvard), SuperMACHO & EHS collaboration

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References for further reading:

- Westerlund, B., 1961, "The Nebulosity around RS Puppis", PASP, 73, 72
- Ortiz, J.L. et al, 2010, "Observation of light echoes around very young stars", A&A ,519, 7
- ESO Press Release: "Light echoes whisper the distance to a star", ESO 0805 (2008)
- Sparks, W. B.; Bond, H.E., 2011; "Light Echo Polarization for Geometric Distance Measurement", ASPC, 449, 242
- Bond, H.E., Sparks, W.B., 2009, "On geometric distance determination to the Cepheid RS Puppis from its light echoes", A&A, 495, 371
- Tylenda, R., 2005; "Evolution of V838 Monocerotis during and after the 2002 eruption", A&A, 436, 1009
- Feast, M.W., 1999; "Cepheids as Distance Indicators", PASP, 111, 775
- Havlen, R.J.,1972; "The nebulosity surrounding the galactic Cepheid RS Puppis", A&A, 16, 252
- Kervella, P., et al., 2008; "The long-period Galactic Cepheid RS Puppis I. A geometric distance from its light echoes", A&A, 480, 167
- Crause, L. et al., 2005; "V838 Mon: light echo evolution and distance estimate", MNRAS, 358, 1352
- Sparks, W. B. et al., 2008; "V838 Monocerotis: A Geometric Distance from Hubble Space Telescope Polarimetric Imaging of its Light Echo", AJ, 135, 605
- van Loon, J. Th. et al., 2004; "Discovery of multiple shells around V838 Monocerotis", A&A, 427, 193
- Kraft, R.P., Schmidt, M.,1963; "Galactic Structure and Galactic Rotation from Cepheids", ApJ, 137, 249
- Voute, R., 1939, "RS Puppis", Annals of the Bosscha Obs. 8, 31
- Westerlund, B. E., 1963; "An OB association in the region of RS Puppis", MNRAS, 127, 71
- http://www.aavso.org/vsots_rspup