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Long-term light curve variations of AGB stars: episodic mass-loss or binarity?

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Abstract. A significant fraction of the stars near the tip of the AGB phase become regular or semi-regular (Mira-type, SRs) pulsators. However, some of these light curves have shown intriguing secondary minima or sharp dips with much longer periods. Although this phenomenon shows some resemblance with the R CrB variables, the light curve is generally symmetric before and after the dip, whereas in R CrB the luminosity recovers slower after its minimum. More recently, high-resolution ALMA CO observations revealed a spiral structure around some of these stars, which suggests the presence of a stellar or sub-stellar companion. In these cases, the long-term light curve minima could be caused by periodic eclipses of the primary by a spiral circumstellar structure, and the long-period would be related to the orbital period. In this paper we discuss the pros and cons of the various proposed scenarios for the long-term minima of pulsating AGB stars.

Keywords. AGB stars, variable stars, binaries, mass-loss

1. Introduction

The asymptotic giant branch (hereafter AGB) is an evolutionary phase when an intermediate-mass star reaches a high luminosity, which favours a strong mass-loss rate (up to $10^{-4} M_{\odot} \mathrm{yr}^{-1}$). A significant fraction of the AGB stars develop radial pulsation in a scale of a few hundreds of days. Pulsation can be regular (the Mira-type variables), semi-regular (SRa, SRb types) or irregular (Lb). The high mass-loss rate often generates a optically-thick dust shell that may obscure (partial or totally) the visual spectrum of the star. The opacity of the dust shell is generally higher in carbon-rich stars (*i.e.* when [C]/[O] > 1), except in the cases where the O-rich AGB star undergoes a very high mass-loss rate (e.g. OH/IR stars, Lépine et al. 1995).

Long-term photometric observations (often limited to visual) of pulsating AGB stars obtained along the last century have revealed various kinds of inhomogeneities in their light curves, such as: variable amplitude and period, occurrence of multiple periods, changing light curve shapes, etc. However, about half of these pulsating stars show an intriguing very long secondary period (Soszyński et al. 2021), and a small fraction of them exhibit deep and sharp luminosity drops that can last one or a few pulsation cycles (Fig. 1). During these events, the visual brightness can decline 5 or 6 magnitudes, and the phenomenon can repeat in regular intervals of many years (between 18 ∼ 37 yrs in Table 1). The vast majority of these objects are C-rich.

In this paper, we discuss the most likely scenarios proposed in the literature to explain these long-term brighness decays, their pros and cons, considering multi-wavelength observations obtained at various spectral and spatial resolutions.

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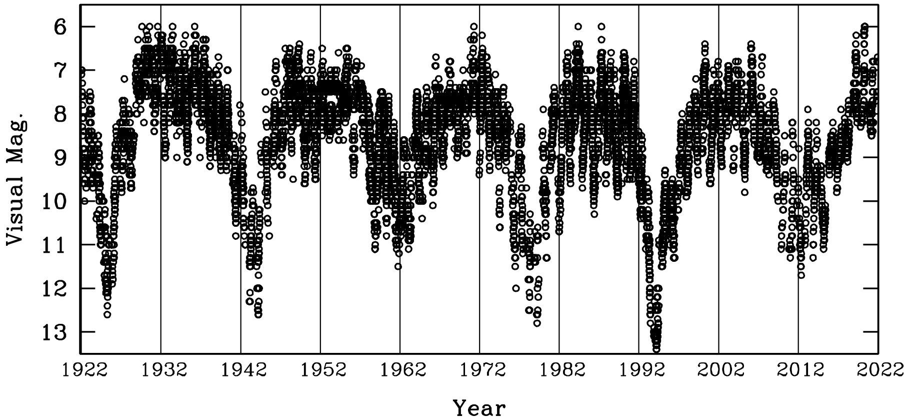

Figure 1. Visual light curve of V Hya, covering a period of 100 yrs, showing its 18-yrs eclipse period. Data collected by the AAVSO.

2. R Lep: the prototype of a new class of variable?

R Lep is a C-rich, regularly pulsating AGB star that has been closely monitored since the first half of the XIX century. According to Mayall (1963), the star "was faint before 1910, then bright until 1949, and definitely faint from 1950 through 1961". Besides R Lep, Mayall (1963) recalls that the light curve of V Hya shows a similar behaviour, and since then other pulsating variables have been added to the list (Table 1).

The case of R Lep is emblematic because some of its eclipses were closely observed, using various techniques. The first polarimetric observations were obtained starting 6 yr after its 1959−1960 eclipse by Serkowski (1966), and then by Kruszewski, Gehrels & Serkowski (1968) and Serkowski (1971). Eventually, Raveendran (2002) obtained long-term polarimetric observations, including the long photometric dim that occurred between 1993−1998. Based on these observations, Raveendran & Kameswara Rao (1989) proposed a correlation between the long-term changes in polarization and the photometric dims observed in the light curve of R Lep. Apparently, polarization follows the intensity of the eclipse, reaching its maximum percentage together with the light curve minimum. Besides, Raveendran (2002) observed that the polarization angle changed abruptly at the beginning of the 1993−1998 eclipse, from $\theta \simeq 45°$ (before) to 28° (from 1993 onwards).

Long-term $JHKL$ photometry carried out by Lloyd-Evans (1997) and Whitelock et al. (2000) indicates that the photometric dims are caused by obscuration by circumstellar dust grains. The rapid change in the polarization angle and the synchronicity between the polarization degree and the light curve suggest that the circumstellar dust that causes the eclipse is condensed near the star, perhaps within a few stellar radii (Clayton, 1992).

3. Possible Mechanisms

Olivier & Wood (2003) cite two major scenarios to interpret the "eclipse" undergone by some AGB stars. In this section we briefly describe their hypotheses.

3.1. *Episodic mass-loss*

Episodic mass-loss, perhaps as a result of a change in the pulsation mode, may result into hydrodynamical or thermal instabilities that can trigger the formation of dust clouds that block the stellar radiation (Winters et al. 1994; Woitke & Niccolini 2005). Hinkle et al. (2002) and Wood et al. (2004) monitored the radial velocity of a

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sample of AGB stars with long secondary periods. They noted two arguments against the hypothesis of a change in the the radial pulsation: (1) the stellar $T_{\rm eff}$ values along the cycle are incompatible with the amplitude of the light curve and the colour indices observed; (2) the large change in amplitude implies a large variation in the stellar radius, and in this case the period of the fundamental (or primary) mode of pulsation would have changed a factor between 1.64 and 1.93 in the cases studied. However, Wood et al. (2004), after analysing MACHO photometric data of a large sample of pulsating AGB stars with secondary (long) periods in the LMC compiled by Wood et al. (1999), did not find any evidence for fundamental period changes. They excluded also the possibility of non-radial pulsations, as they are incompatible with the large observed radial velocity amplitudes and their long periods.

Although the mechanism of episodic mass-loss is not fully understood, there are solid evidences that it operates in some AGB stars, provided the object is observed at high spatial resolution. For example, using interferometric observations at 11 μm, Hale et al. (1997) observed a periodic dust shell structure around the AGB star IK Tau at 100, 320 and 570 mas, which correspond to intense mass-loss events occurred in intervals of 12 yrs (whilst the stellar pulsation period is $470^{\rm d}$). Unfortunately, high spatial resolution observations are available only for few AGB stars with long-period photometric dims (Sect. 5).

Whatever its cause, if episodic dust ejection operates among AGB stars with long-period dims, they must be asymmetric in order to explain the change in the polarization angle observed after the beginning of the event (Sect. 2). In this scenario, the circumstellar material expelled by the star forms an aspherical structure around the star, perhaps a clump or a disc. As the circumstellar shell moves away, its opacity decreases and the light curve returns to its pre-obscuration status.

3.2. *The binary hypothesis*

The second possibility is that the AGB star is a member of a **binary system**, and its light is obscured by a cloud of dust and gas associated with an orbiting companion (Wood et al. 1999; Soszyński & Udalski 2014). Binarity is a common phonomenon among AGB stars, but detecting visually the secondary component is generally unfeasible because the high-luminosity primary outshines its low-luminosity companion. Fortunately, in some cases this limitation can be overcome. For example, if the secondary component is relatively hot or it exhibits a chromosphere, a far-UV excess can be detected (Sahai et al. 2008; Ortiz et al. 2019). Alternatively, far-UV excess could be originated in an accretion disc around the secondary, and the UV continuum of some of these AGB stars with far-UV excess was observed to exhibit "flickering" on very short timescales (< 20 s), and the UV spectra show emission lines (Siv, Civ) with P-Cygni profiles. Altogether, these UV characteristics have been interpreted as a strong evidence of a hot accretion disc around a degenerate companion that remains overlooked in the visual spectral range (Sahai, 2018).

The far-UV features described above are sometimes accompanied by X-ray emission, even though large-scale X-ray surveys are still too shallow to allow a firm conclusion about the occurrence of X-rays among far-UV AGB stars. Two possibilities have been proposed to explain the X-ray emission associated with AGB stars: (1) coronal emission of its main-sequence or sub-giant companion; (2) a hot accretion disc around a white dwarf companion (Jorissen et al. 1996; Sahai 2015; Ortiz & Guerrero 2021). Stellar coronae are normally found over a wide variety of spectral types and luminosities, except in stars situated at the top-right corner of the HR diagram, where AGB stars belong

Table 1. Some examples of AGB stars showing regular "eclipses" or "luminosity dims".

Star's name	$P_{\rm puls}$ (days)	$P_{\rm fade}$ (yrs)	Spectral Class	References
EV Eri	226	?	C-J	Whitelock et al. (2006)
R For	387	37	C4,3e	Feast et al. (1984)
V Hya	530	18	C-N:6	Baize (1962)
R Lep	438	35	C7,6e	Lloyd-Evans (1997)
II Lup	575	19	C	Feast et al. (2003)
L_2 Pup	140	?	M5eIII	Bedding et al. (2002)

(Linsky & Haisch 1979; Ayres et al. 1981). Thus, since AGB stars do not emit X-rays, these sources must be extrinsic to the AGB star.

In the case the AGB is binary, the mass expelled by the primary component orbits the system, forming an asymmetrical envelope that is sometimes observed in the mid-infrared and radio observations (Feast et al. 2003). More recently, the binary hypothesis has been reinforced by radial observations of the star V Hya (Table 1). Monitoring of its radial velocity showed that the velocity of its primary component equals that of the centre-of-mass just in the middle of the eclipse, i.e. when the companion is in front of the AGB star (Planquart et al. 2022).

4. Phenomena associated with the eclipse

Besides the sharp luminosity decline, the main phenomena associated with the luminosity drop are summarized below:

• **Infrared Excess** is commonly observed simultaneously with the luminosity drop. Unfortunately, photometric monitoring of an eclipse has never been obtained at wavelengths beyond the L' band in the near-infrared. Near-infrared excess has been associated with the differential extinction caused either by the episodic mass-loss of the primary or debris around a secondary component.

• **Spectral changes** are observed during the eclipse. The C_2 molecular bands between 4700 $\sim$ 4730 Å and 5100 $\sim$ 5200 Å, and the SiC_2 band near 4900 Å, all of them in emission, were observed to increase their intensity during an eclipse of R Lep (Lloyd-Evans 1997).

• **The Degree of Polarization** was observed to decrease following the end of an eclipse of the star R Lep. Besides, there was a change in the polarization angle, when the pre-eclipse and post-eclipse angles are compared. This has been interpreted as the presence of asymmetric material around the star. It is not clear whether this asymmetry is caused by an asymmetric mass-loss of the AGB star or by the presence of a companion.

5. High-resolution imaging

Recent high spatial resolution observations obtained at various wavelengths have revealed the presence of asymmetric structures in the neighbourhood of the AGB star. For example, near-infrared images of II Lup (Table 1) obtained by Lykou et al. (2018) in the K_s, L and M bands showed circumstellar non-coincident structures with different shapes and sizes. However, these features are not found in all stars of this kind. For example, near-infrared, high spatial resolution images of R Lep showed no sign of asymmetry (Paladini et al. 2017).

A wider picture of II Lup was obtained by Lykou et al. (2018) at radio wavelengths, using the ALMA facility. Observations revealed a gigantic spiral structure detected at the CO (J=1−0) line, extending up to 23 arcsec from the star, amounting to 12 windings separated by $\sim$1.7 arcsec from each other. Their results have been interpreted as a

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strong evidence of binarity, and the spiral of gas was supposed to have been formed by the stellar wind of the II Lup, driven by the mutual movement of both members of the system around the centre-of-mass. Based on the ALMA data an orbital period of 128 yr was derived for that system, very different from its "eclipse" period of 19 yr (Table 1). The discrepancy suggests that the period of the deep dims may not be related to the orbital period of the system.

There are other binary AGB stars that exhibit a disc or a spiral structure, but their light curves look standard. ALMA high-resolution observations of the binary AGB star R Aqr (Ramstedt et al. 2018) revealed a ring-like structure in the orbital plane, which is an evidence for an episodic mass-loss event that occurred 100−50 yr ago. Another example, π^1 Gru, is a binary S-type AGB star with a secondary situated at ∼400 AU and an orbital period of 330 yr. ALMA images of ^{12}CO (J=3−2) revealed a spiral structure as well as a bipolar outflow perpendicular to the plane of the spiral (Doan et al. 2020). The bipolar structure seems to have been formed during an episodic mass-loss event that lasted 10−15 yr. In spite of the morphological similarities between R Aqr, π^1 Gru and II Lup (a disc or spiral structure, intense mass-loss episodes), the former two stars do not show evidence of undergoing luminosity dims, either because these phenomena are not correlated, the orbital angle of the system relative to the observer does not produce eclipses, or the period between the luminosity dims is too long to be noticed.

6. Conclusions and Perspectives

Considering the evidences gathered to this date, it is not possible to draw a single scenario that definitively explains the variety of observational characteristics observed. It is possible that a fraction of the "eclipsing AGBs" consists of binary systems, whereas other stars may be single. Detecting the secondary by their UV excess (if the binary hipothesis is valid) is not an easy task, because the high opacity of the circumbinary material can absorb most of the UV flux emitted by the secondary or its accretion disc. Therefore, observations obtained at high spatial resolution, especially ALMA, may become paramount to detect evidence of binarity. Considering the small number of "eclipsing AGBs" a special effort must be done to observe every future eclipse of this kind of object.

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