On the nature of VX Sagitarii: Is it the first galactic super-AGB star found?

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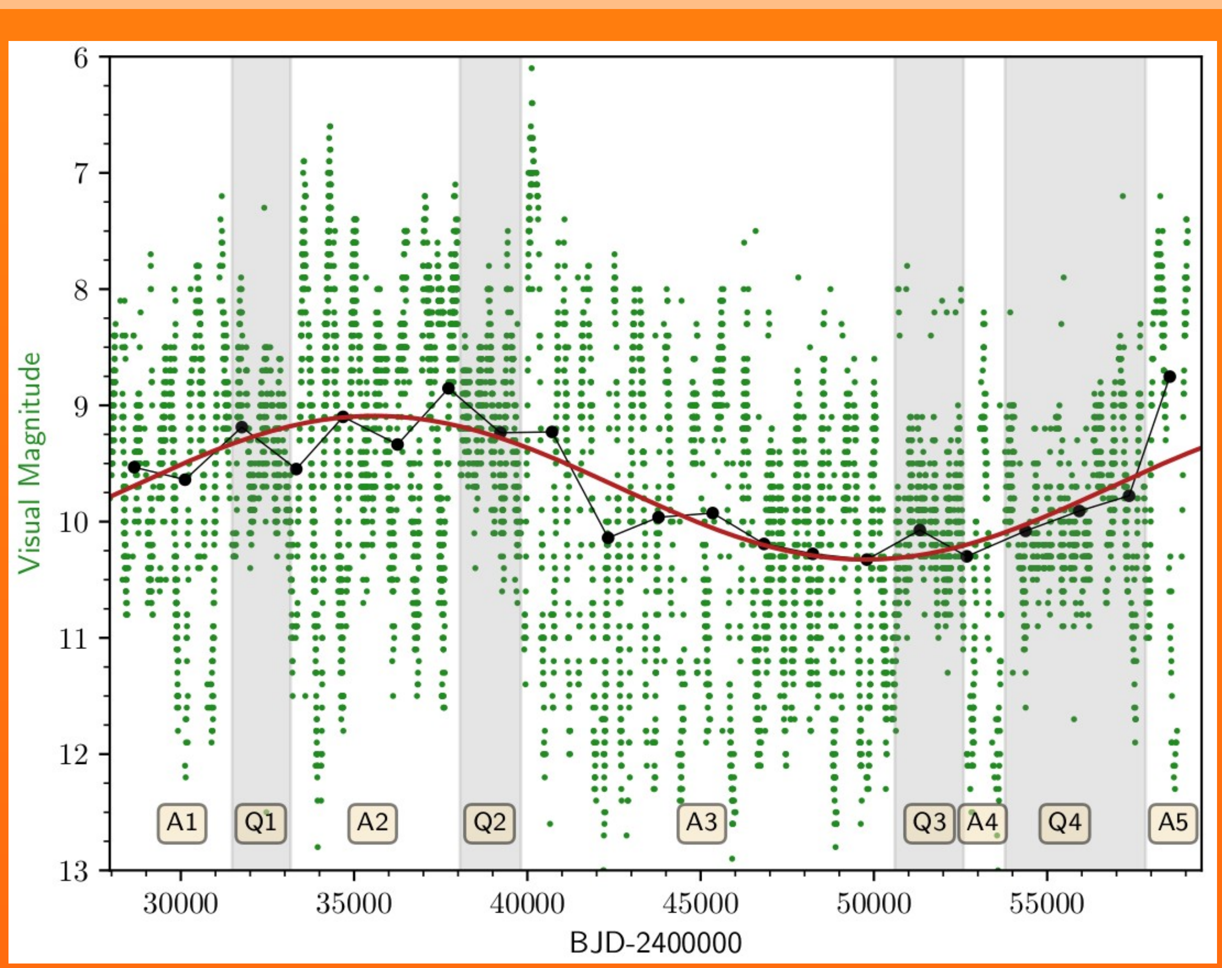
Background: After the main sequence, moderately high-mass stars (Initial mass between ~10 and 25 $M_\odot$) will evolve into red supergiants (RSGs, [1]), while intermediate-mass stars will evolve into red giants and, later, those massive enough (4 to 10 $M_\odot$) will become oxygen-rich asymptotic giant branch (AGB) stars [2]. Despite their external similarities between AGB stars and RSGs (both groups have similar spectra and effective temperatures, and thus colours), their evolutionary paths and deaths are completely different due to their different internal structures. The main external difference between these groups is their luminosity. Typical RSGs have absolute bolometric magnitudes (Mbol) between -9 and -7 mag. Average AGB stars usually have luminosities far below that. Only the most luminous AGB stars reach bolometric magnitudes (M_{bol}) as high as -8 mag and very few of them are known [3,4].

This work: We studied VX Sagitarii (VX Sgr), an extremely luminous star (M_{bol} between -9.3 and -7.8 mag depending on the distance assumed). Due to its high luminosity, this star has been considered classically as an extreme and peculiar red supergiant. Here, we demonstrate that it cannot be a RSG, but a massive AGB star.

Observations: We obtained high-resolution spectra for VX Sgr on 11 different epochs between April 2016 and June 2018, using STELLA echelle spectrograph (@1.2 m robotic telescope STELLA, resolving power of 55k) and the Ultraviolet and Visual Echelle Spectrograph (UVES @Very Large Telescope, resolving power of 110k). We derived radial velocities (RVs) and effective temperatures (T_{eff}; by using the SteParSyn tool [5]) for these spectra.

Photometric serie: The light curve of VX Sgr has been recorded (in visual magnitudes) by the American Association of Variable Star Observers since 1935. We used this data in this work. We studied the periodogram of VX Sgr. We confirmed its main period of 757 d. The photometric variation associated with this period is typical of a Mira star (a pulsating AGB star). We also found a secondary peak at 28,279 d (~77 a). Although this peak cannot be confirmed as truly periodic, its correlation with the average magnitude during the 85 years covered is extremely good (see Fig. 1).

Figure 1: Lightcurve of VX Sgr from 1935 up to 2020. Green dots are the visual magnitudes recorded. Black dots represent a 2-periods binning of the light curve The red curve is a sinusoidal toy model with a ~ 77 a period.



Spectral features:

→We found strong Rb I lines in VX Sgr. The Rb I overabundance is typical of evolved AGB stars [16,17,18], but the Rb I enrichment mechanism (S-process+dragging) does not happen in RSGs (Fig. 2). The presence of strong circumstellar (CS) Rb I lines in VX Sgr was already reported [16], but we also observed the photospheric lines which in VX Sgr are usually concealed by CS Rb I emission [16,19]). Although it was not possible to calculate the Rb abundance, it is known that it is correlated with the expansion velocity of the CS OH masers (V_{exp}(OH)) [16]. The AGB stars with the highest abundances measured in [16] have V_{exp}(OH)=16 km/s. VX Sgr has a V_{exp}(OH) between 20 and 23 km/s [12,20].

→During the light maximum, all the strong atomic lines in the spectra were doubled. This effect is caused by shockwaves moving through the atmosphere, and is typical of Mira stars. This confirms the nature of the main photometric variation as caused by pulsations.

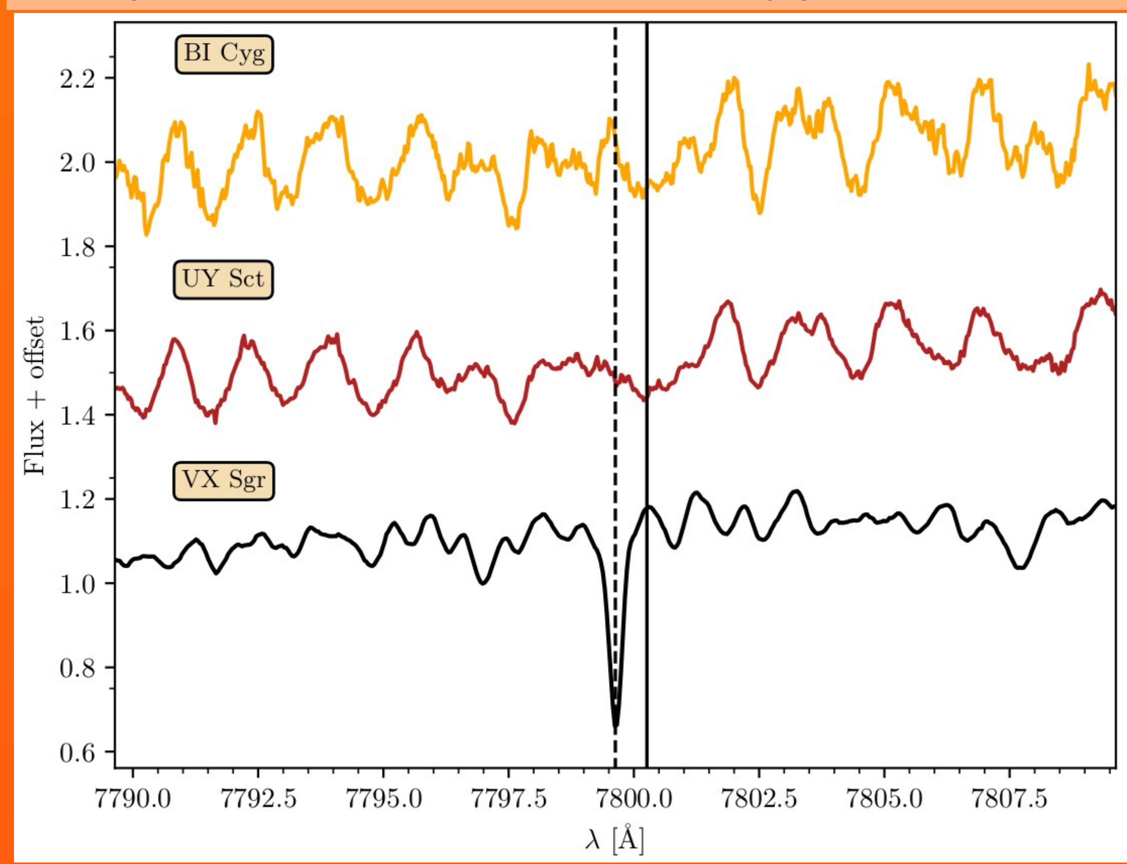


Figure 2: The Rb overabundance in VX Sgr is clear when its Rb I line at 7800 A is compared with the same region in other RSGs with similar luminosities and spectral types to those of VX Sgr.

Distance: The distance to VX Sgr was calculated in several works and by different methods: belonging to the Sgr OB1 association (1.5 to 1.7 kpc [6]), photometric parallax (1.5 kpc [7]), direct parallax (by Gaia; $1.36^{+1.02}_{-1.41}$ [8]), by H_2O masers parallax (1.7±0.3 [9], 1.8±0.5 [10], and $1.56^{+0.11}_{-0.10}$ kpc [11]) and by SiO masers parallax (1.57 ± 0.27 [12], and 1.10 ± 0.11 kpc [13]). We decided to assume a weighted (by the inverse of the errors) average distance for this work: **1.44 ± 0.19 kpc.**

Luminosity: We used the average T_{eff} we obtained (3370±100K) together with the average distance and the average angular diameter calculated for VX Sgr of 8.76 ± 0.4 mas [14,15]. The result is **M_{bol} = −8.6 ± 0.6 mag**, far higher than most luminous AGB star (M_{bol} ~ -8 mag).

Conclusions:

Nature of VX Sgr: Despite its high luminosity, the Rb I and the duplication of lines found on VX Sgr are incompatible with being a RSG. Thus, VX Sgr has to be the most luminous AGB star known to date. The absence of Lithium (typical of early-stage AGB stars) together with the strong Rb I lines, suggest that **VX Sgr is an evolved AGB star**, probably close to the end of its thermal pulsing phase.

Mass of VX Sgr: The high Rb abundance underlying the observed features in VX Sgr also supports that it is a high-mass AGB star. In fact, the luminosity of VX~Sgr is above what is predicted for AGB with 9-10 $M_\odot$. Although most models predict that stars with initial mass above 10 $M_\odot$ will evolve into RSGs [21], but some suggest that under the right conditions, stars with initial mass as high as 12 $M_\odot$ [17,22] may evolve into AGB stars. Thus it is entirely possible that the initial mass of VX Sgr is higher than 10 $M_\odot$, but it can not be settled by our data. It is also possible that models are underestimating the luminosity of high-mass AGB stars.

Thermal Pulses: Models [21] predict for AGB stars that the time between thermal pulses is lower at higher stellar masses. Above 9 $M_\odot$ it can be as short as a few decades. Thus it is possible that the observed periodogram peak obtained at ~77 a is the effect of a thermal pulse. This relation cannot be proven by the current data, but it is the only explanation available for such a long signal.

A super-AGB star? AGB stars massive enough (>8 $M_\odot$) may ignite their carbon cores before entering the thermal pulsing phase, becoming super-AGB stars. It has been proposed that super-AGB stars should present an extremely high luminosity and a high overabundance of Rb. From a theoretical standpoint, it is very likely that VX Sr is a super-AGB star since both criteria are met. A number of candidates to super-AGB stars have been identified in the Small Magellanic Cloud [3,23], but VX Sgr is more luminous than any other candidate. Thus, we think that VX Sgr can be considered the strongest candidate to super-AGB star, and the first located in the Milky Way.

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