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Investigating the true nature of the red hypergiants.

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Abstract

Red hypergiants (RHGs) are evolved high-mass stars with very low temperatures and extreme mass-loss rates, whose luminosities are close to the empirical upper luminosity boundary. Classically, these stars have been considered as a peculiar group among red supergiants (RSGs), as they have supposedly evolved from very high initial masses (above 30 $\mathrm{M}_{\odot}$), far above the 10 to 25 $\mathrm{M}_{\odot}$ expected for most RSGs. However, evolutionary models do not offer a satisfactory explanation for the observations of RHGs, and a new scenario has been proposed to explain these stars, that they are regular RSGs which are in their last stage. In order to understand the true nature of these stars, we have performed a spectroscopic following of some well-known galactic RHGs along two years, covering approximatively one of their variability perdiods. Our results on the most remarkable star in our sample, VX Sgr, were unexpected and show that there is yet much to understand about these stars.

1 Introduction

Red supergiants (RSGs) are evolved stars with moderately-high initial masses, between 10 and 40 $\mathrm{M}_{\odot}$ ([3, 7]). These are the largest stars known, with radios between 400 and 1 700 $\mathrm{R}_{\odot}$, and characterized by their low effective temperatures (T_{eff}), which implies late spectral types (SpTs), mainly M in Galactic RSGs, and their very high luminosities, in the range of $\log(\mathrm{L}/\mathrm{L}_{\odot}) \sim 4.5-5.8$. Among these stars, there is a small subpopulation that present even more extreme characteristics (see Table 1), known as "OH/IR M-type supergiants", "extreme red supergiants", or "red hypergiants" (RHGs).

There are two scenarios for the origin of RHGs. The classical interpretation, based on the prediction of evolutionary models([7]), says that these stars come from the evolution of stars with initial masses between 30 and 40 $\mathrm{M}_{\odot}$ ([17]). However this scenario has some problems. Evolutionary tracks in the range of 30 and 40 $\mathrm{M}_{\odot}$ do not reach temperatures lower than those of lower masses [18]. Thus, it is not easy to explain why they present much later

Table 1: Comparative between "average" RSGs and red hypergiants.

Property	Average RSGs	Red hypergiants
Luminosity $[\log(L/L_{\odot})]$	$\sim 4.7-5.1$	$\sim 5.3-5.8$
Mass-loss $[\log(M_{\rm loss}/M_{\odot})]$	~ -6	~ -5 to -4^{a}
Spectral type	Centred distribution around M2[b]	M4 or later[c]
Spectral variability	$\sim$ 1 subtype or less	From 2 subtypes up to 6[d]
Photometric variability	$\sim$ 1 mag in V	$2-3$ mag in V
	< 0.5 mag in I	> 0.5 mag in I

[a]In addition, RHGs also present H_2O masers while normal RSGs do not.
[b]Most RSGs between M0 and M4
[c]As late as M10
[d]From M4 to M10

SpTs. Moreover, according to the models, they stay only for such a short time at the coolest end of the tracks that it would be impossible to observe any of them ([6]). A new scenario was proposed a few years ago. It is based on observations of clusters rich in RSGs whose age correspond to stars with initial masses in the range 15 and 20 $M_{\odot}$. Sometimes these clusters also host a few (one or two) RHGs, which are expected to be already dead according to the first scenario ([16, 2]). Therefore, this scenario proposes that evolutionary models are underestimating the luminosity of RSGs at the end of their lives, and that RHGs are the last and brief stage of RSGs.

Our approach to RHGs is motivated by the lack of modern studies about these stars, as the only recent works are about their envelopes. Thus, the information about their chemical composition and spectral variability is scarce. To understand better these stars, we observed a significant sample of them (8) with high resolution spectroscopy along one of their photometric periods (typically about two years). For this, we used the spectrograph mounted on the robotic telescope Stella (1.2 m, R$\sim$ 55 000 from 3 900 to 8 700 Å). We observed our targets with a frequency of one observation every $2-3$ months during two years. Now we have almost finished the analysis of the most extreme star in our sample, VX Sgr, and we have began the analysis of the other seven.

2 Analysing VX Sgr

2.1 Data

VX Sgr has been studied in many works. It is known to present the largest SpT variations found in a RSG ([11, 15]), from M4 up to M10, along a period of about 2 years (732 d according to [13], and 750 d [12]). VX Sgr also presents variable veiling (weakened atomic lines) and activity in H lines ([11]). Its photometric variation has an irregular amplitude, alternating quiescent periods (amplitudes of $\sim$ 2 mag) with active periods, when it varies up to 6 mag ([12]).

The distance to VX Sgr has been calculated through different methods, an it ranges from 1.1 to 1.8 kpc, but there is not a definitive value. Depending on the method, $T_{\rm eff}$ and the distance used, its bolometric magnitude vary from $M_{\rm bol} = -8.4$ ([4]) to $M_{\rm bol} = -9.1$ mag ([1, 14]).

We have observed VX Sgr at 8 different times during the last two years with the Stella Spectrograph. For each spectrum collected we obtained its $T_{\rm eff}$, SpT and radial velocity (RV). In addition, we observed it on three extra epochs with UVES (mounted on the Very Large Telescope), but from these spectra we could not obtain the $T_{\rm eff}$, due to the spectral range covered.

2.2 Which is the true nature of VX Sgr?

Examining the spectra we found present the Rb lines at 7 800.3 and 7 947.6 Å. In the subsequent revision of bibliography, this fact was already reported by [8], in a work about asymptotic giant branch (AGB) stars which has not been accounted in any work about VX Sgr. Rb is an s-element which is only present in the atmospheres of AGB stars, evolved stars with initial masses from ~ 1 to $10\,{\rm M}_\odot$. Moreover, their abundances are specially high in AGb with high masses ($> 4-5\,{\rm M}_\odot$; [8]) Thus, the presence of Rb is not compatible with the assumption that VX Sgr is a RSG.

Nonetheless, it is not straightforward that VX Sgr is an AGB star. The highest-luminosity AGB stars observed have $M_{\rm bol} \sim -8$ mag ([10, 9]). This is in agreement with the highest luminosities predicted for AGB stars, which are expected to be reached by those with highest masses and lower metallicities ($M_{\rm bol} \sim -8.2$mag for masses from $M \sim 8$ to $M \sim 9{\rm M}_\odot$; [5]). However, the range of $M_{\rm bol}$ obtained for VX Sgr goes from -8.4 to -9.1 mag and it is not a low-metallicity star. Thus, only one key point is clear: VX Sgr is not an usual RSG neither a typical AGB star. However, it is more likely that it is an extreme AGB star, than a high-mass RSGs, as it is easier to explain an extreme luminosity in an AGB star, than the presence of Rb in a RSG. Also, a new question arises from this: is VX Sgr an isolated anomaly among high-mass hypergiants or are all the others intermediate-mass stars?

2.3 Unexpected results

The presence of Rb lines is not the only unexpected result: they present two anomalies. The first one is that the both lines are shifted toward the blue. This shift has been detected before in a few other AGBs and has been explained assuming that the Rb lines have a circumstellar origin ([19]). The second anomaly has not been observed before. In one of our epochs, in addition to the the blue-shifted Rb lines, another pair of Rb lines appeared on the position expected for the phostospheric Rb lines. We think that the photospheric component in the Rb lines is usually hidden by the P-cygni emission of the circumstellar component. According to the models calculated by [19] such emission depends on the density of the envelope. Therefore, a reduction of the P-Cygni emission can be caused by a decrease of the envelope density, which probably is related to spectral and photometric variations.

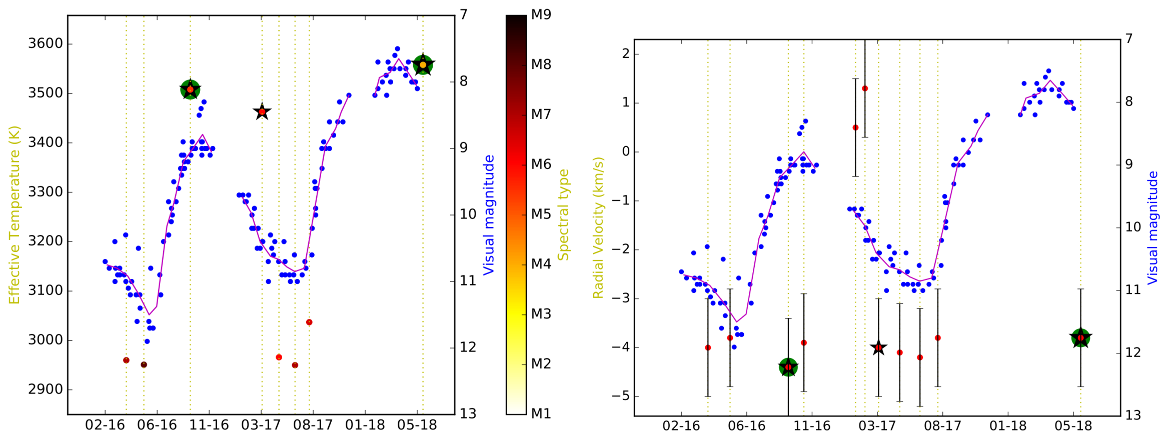

Figure 1: Light curve of VX Sgr. Blue dots are visual magnitude observations from AAVSO and the magenta line indicates the average value (magnitude scale is indicated in the right axis). Epochs with significant veiling are indicated by background black stars, while green halos indicate H emission. The Rb anomaly (see text) happened on 04/04/17. Reddish points are our spectral data and their corresponding values are given in left axis: Fig.1a (left): $T_{\rm eff}$ and point colors represent the SpT. Fig.1b (right): Radial velocity.

To study the variations of VX Sgr we used the data collected by AAVSO[1] for the visual band. We compare the light curve with our own data in Figure 1. The light curve of VX Sgr has been linked to the formation and evaporation of molecular layers, mainly TiO ([12]). This is coherent with the variation of the SpT, as later types, which have more intense TiO bands, happen at minimum light while earliest types happen at maximum light (see 1a). In Mira stars (which are also AGB stars), these variations are caused by the pulsation of the star. However, we found the RV of VX Sgr to be constant at −4 km/s (see Figure 1b). However, there is a sudden variation in the spectra obtained in January and February 2017. These spectra show very different velocities, and thus happens not long before the Rb anomaly (April 2017). This does not seem related to a periodic pulsation, but a sudden change in the star.

2.4 Period analysis

There are two more hints that point toward a sudden change in VX Sgr. Firstly, we used the 83 years of AAVSO data to calculate the period, obtaining 750 d (consistent with [12] results). However, this does not match with the last two years. Only 520 d passed between the two last maxima, and 450 d between last to minima. This anomaly supports the idea that something changed in VX Sgr that altered its usual periodic variation. Secondly, the last maximum light, at the beginning of 2018, has reached the lowest magnitudes since 1968, almost 1.5 mag brighter than the previous one in 2016.

[1]American Asociation of Variable Star Observers

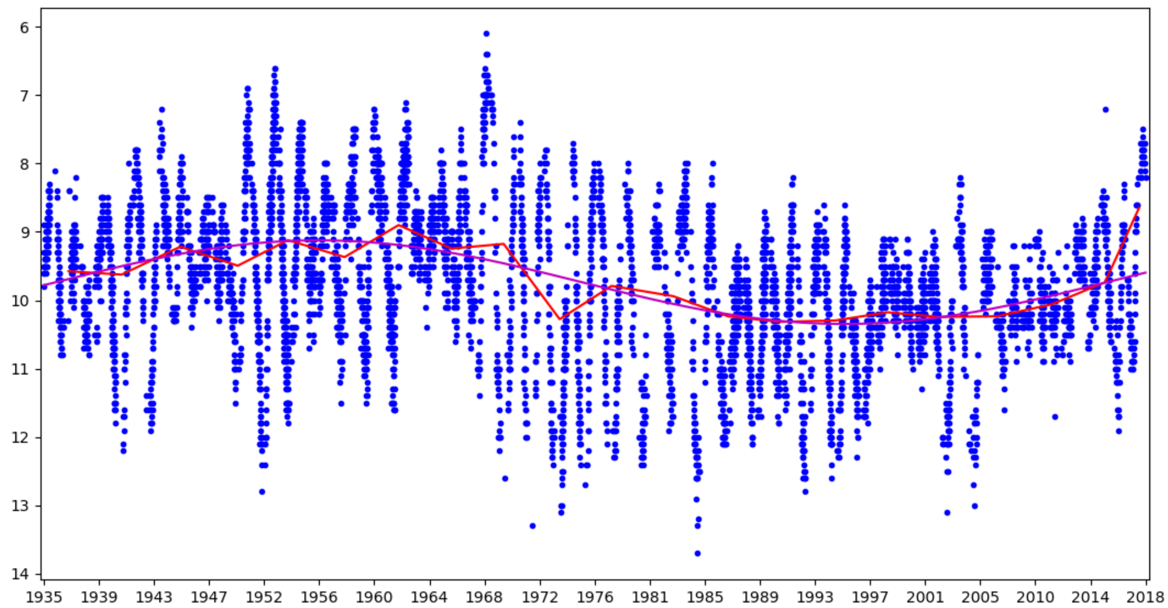

Figure 2: Light curve for VX SGr. Blue dots are visual magnitude observations from AAVSO. The red line indicate the average value, while the magenta line is a sinusoidal model with $P \sim 27\,600$ d.

When we analysed the light curve, we found a tentative secondary ultra-long period of $\sim 27\,600$ d (~ 75.5 a), never detected before. We think that it is an intrisic variation, as there are no signs of an unknown companion in the circumstellar envelope ([12]). When we examined the 83-year light curve, we found that the only maximum lights in the main period similar or brighter than the last one, are those happening around during the last maximum in the secondary period, as shown in Figure 2. According to our fit of a 75-year period, VX Sgr is about to reach (less than one decade away) the maximum in this secondary period. Thus, we speculate that whatever are the processes drive this secondary period, they are related to the violent change that we have observed.

3 Conclusions

The analysis of VX Sgr is almost finished, but we do not have definitive conclusions yet. The detailed analysis and our conclusions will be published in Tabernero et al. (in prep). However, this is only the beginning. Many new questions about this star have arisen from our observations. To answer them we are performing a spectroscopic follow up programme with much higher time resolution (one observation each ~ 10 d), that will allow us to examine in much higher detail any other sudden episode like the one happened in 2017. Also, we are still analysing the other RHGs. From that work we would be able to stablish whether VX Sgr is an isolated case among RHGs or not, and the nature of these mysterious stars.

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