LBVs, hypergiants and impostors — the evidence for high mass loss events

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LBVs, hypergiants and impostors — the evidence for high mass loss events

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Abstract. Mass loss from massive stars is common. It plays an important role in the evolution of stars above about 20 $M_\odot$. In the massive hot stars the winds and mass loss are driven by radiation pressure on the lines. The mass loss mechanism in post-main sequence red supergiants is still debated but pulsation and convection play a role. In this short talk, I am emphasizing the evidence for high mass loss episodes in evolved massive stars with specific examples such as VY CMa, IRC +10420 and the giant eruptions of LBVs, the possible origin of these episodes, and their importance in the final stages of massive star evolution. By analogy with the less massive AGB stars, I suggest that VY CMa is a candidate for a second red supergiant stage.

1. Introduction

We observe evidence for episodic high mass loss events across the upper HR Diagram ranging from the non-terminal giant eruptions of very massive stars such as eta Car, enhanced mass loss in the LBV stage, and in the evolved warm and cool hypergiants near the upper luminosity boundary. I'll begin this brief overview with the cool side of the HR diagram with highlights of recent work on the mass loss histories of the extreme red supergiant VY CMa and the post-red supergiant IRC +10420.

2. The warm and cool hypergiants

A few highly unstable, very massive stars lie on or near the empirical upper luminosity boundary in the HR diagram. In this paper I use the term hypergiant for the evolved stars that lie just below this upper envelope with spectral types ranging from late A to M. They represent a very short-lived evolutionary stage, characterized by high mass loss and eruptive events. Many of them are strong infrared sources and powerful OH masers.

2.1. The recent mass loss history of VY CMa

The powerful infrared source and OH maser VY CMa is one of the most luminous and largest evolved cool stars known. With its very visible asymmetric nebula combined with its high mass loss rate, VY CMa is a special case even among the cool hypergiants that define the upper luminosity boundary in the HR Diagram. Multi-wavelength HST/WFPC2 images of VY CMa [1] reveal a complex circumstellar environment (Figure 1) dominated by three prominent arcs plus bright clumps of dusty knots near the star, all of which are evidence for multiple and asymmetric mass loss episodes. The random orientations of the arcs suggested that they were produced by localized ejections, not aligned with an axis of symmetry.

Figure 1. The multi-color HST visual image of VY CMa [1]

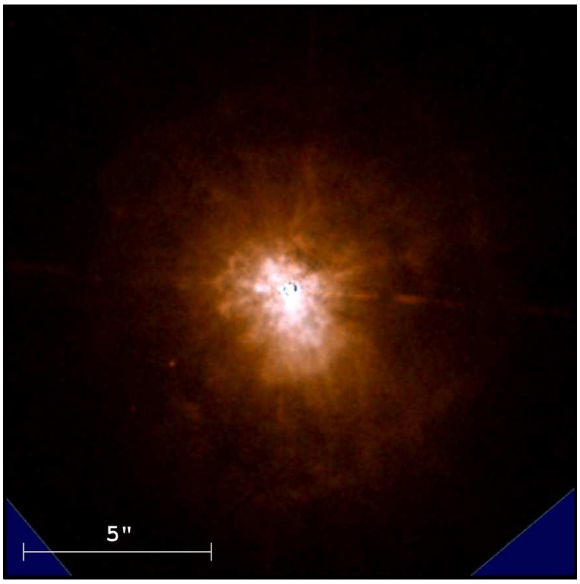

Figure 2. The multi-color HST visual image of IRC +10420 [10]

Second epoch HST/WFPC2 images to measure the transverse motions, which when combined with the Doppler velocities [2], provide a complete picture of the kinematics of the ejecta including the total space motions and directions of the outflows [3]. The arcs and clumps of knots are moving at different velocities, in different directions, and at different angles relative to the plane of the sky and to the star, confirming their origin from eruptions at different times and from physically separate regions on the star. They were ejected in separate events over the past 800 years. The clumps and arcs are massive, with masses on the order of few $\times\ 10^{-3}$ $M_{\odot}$ [4]. This activity could be due to magnetic/convective regions and events analogous to solar activity, i.e. "starspots". Starspots and large surface "asymmetries" have been observed on several stars including Betelgeuse and other red giants, AGB stars and supergiants. The magnetic field strength has now been measured in the ejecta of many of these stars from their OH, H_2O, and SiO masers[5]. For VY CMa they imply surface field strengths of the order of 200 − 400 G. Large-scale convective activity may thus be a cause of high mass loss episodes in evolved, luminous cool stars leading to the formation of intricate arcs and loops as the shocks move through the ejecta from the star's more quiescent outflow.

Long-wavelength (11–37μm) imaging with SOFIA reveals a cooler component with the same asymmetric nebula seen in the visible (Figure 3) but the lack of cold dust at much greater distances indicates that its high mass loss is limited to the last 1200 years [6].

VY CMa also has a unique chemistry compared to other red supergiants. Twenty different molecules including carbon compounds have been identified in its ejecta [7,8]. Many of these molecules are found in the massive arcs and may be produced by shocks in the outflows. In addition, VY CMa has an unusually high C^{12}/C^{13} ratio for an O-rich supergiant[9]. Its chemistry plus it unique circumstellar environment leaves us with some interesting questions about VY CMa's evolutionary state.

2.2. IRC +10420 – two high mass loss periods

IRC +10420 is a powerful infrared source, the warmest maser source known and in the past 30 years or so its apparent spectral type has gone from late F-type to a mid-A. HST/WFPC2

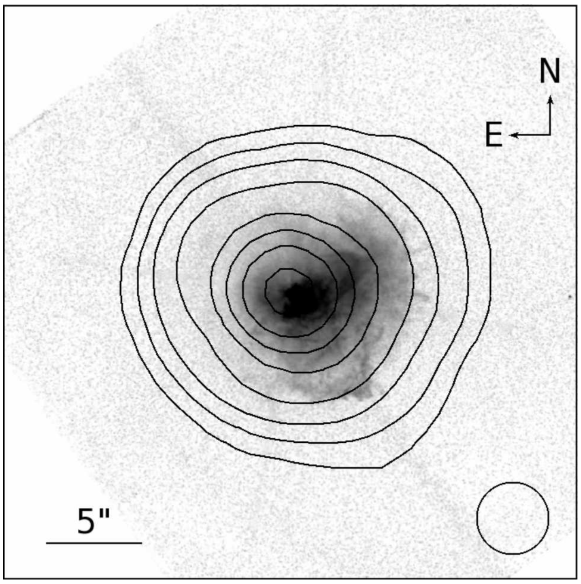

Figure 3. The SOFIA/FORCAST 37μm contours overlaid on the HST visual image, in Figure 1. The circle is the 37μm beam size. The extensions to the NW and SW correspond to the direction of ejection of the NW Arc and Arc 1 [2,3].

images [10] reveal a complex circumstellar environment (Figure 2), with a variety of structures including condensations or knots, ray-like features, and several small, semi–circular arcs or loops within 2" of the star, plus one or more distant reflection shells. These features are all evidence for high mass loss episodes during the past few hundred years. Like VY CMa, the circular polarization of its OH masers imply the presence of magnetic fields in its ejecta with a surface field of 300 – 400G at the star.

Following the example from VY CMa, Tiffany et al.[11], measured the transverse motions of numerous knots, arcs, and condensations in its inner ejecta from second epoch *HST/WFPC2* images. When combined with the radial motions for several of the features, the total space motion and direction of the outflows show that they were ejected at different times, in different directions, and presumably from separate regions on the surface of the star. These discrete structures in the ejecta are kinematically distinct from the general expansion of the nebula and their motions are dominated by their transverse velocities. We find that they are all moving within a few degrees of the plane of the sky. We are thus viewing IRC +10420 nearly *pole-on* and looking nearly directly down onto its equatorial plane. This result is confirmed by independent interferometry [12] and the polarimetry [13].

Recently Shenoy et al. [6] found that IRC +10420's spectral energy distribution at the long wavelengths (11 - 37 μm) from SOFIA/FORCAST imaging cannot be explained by a single mass loss rate. A substantial change in the rate of mass loss that occurred in the past several thousand years is required. Although the transition was very likely gradual, at least two high mass loss periods are required. The first, from about 6000 years ago ago with a very high mass loss rate of 2×10^{-3} $M_\odot$ per year, dropped to about 10^{-4} $M_\odot$ per year beginning about 2000 years ago. We suggest that this change in the mass loss rate is due its post-red supergiant evolution to warmer temperatures.

2.3. The mass loss mechanism and the evolutionary state

Mass loss from red giants and red supergiants (RSGs) has been known since the 1960s, but the mass loss mechanism for red supergiants is still not understood. The leading processes have included radiation pressure on grains, pulsation and convection. Pulsation and dust-driven winds have been successful at explaining the mass loss of the Miras and AGB stars which are fundamental mode pulsators, but are not adequate for the less variable RSGs with their very extended low density atmospheres.

The defining signature of mass loss in RSGs is the presence of circumstellar dust usually revealed as excess radiation in their spectral energy distributions (SEDs) from the silicate emission features at 10 and 20 μm. To a first order, the strength of the silicate emission feature appears to be correlated with the luminosity and apparent temperature as revealed by the spectral type; i.e, the higher the luminosity and later the type (or cooler the star) the stronger the silicate emission and the larger the infrared excess. But the measured mass loss rates at a given luminosity have a large scatter of 10 to 100 times [14], suggesting that other factors are important such as the mass loss mechanism or evolutionary state.

Ground and space-based high resolution imaging and interferometry of evolved massive and luminous stars are transforming our view of circumstellar ejecta, mass loss and the mass loss mechanism in evolved stars. The discovery of large-scale surface asymmetries or hot spots on the surfaces of red supergiants, which vary on timescales of months or years, lends support for convection as an important mechanism for the RSGs. The massive arcs and clumps of knots in the ejecta of VY CMa and IRC +10420, plus the presence of magnetic fields in their ejecta and in other RSGs and AGB stars, suggest that *enhanced convective activity together with magnetic activity may be important for these high mass ejections.*

So, why not more VY CMa's?

There is an observed correlation for increased mass loss with increasing luminosity and cooler temperatures among the red supergiants. Do RSGs evolve through the red supergiant stage getting apparently cooler with more extended envelopes and higher mass loss rates? Or like lower mass stars, could there be more than one RSG state? For example, a post-RSG warm hypergiant could evolve back to the red supergiant stage a second time becoming an extreme RSG, a VY CMa. With its massive arcs and clumps and evidence for extreme activity plus its peculiar chemistry with carbon compounds, VY CMa is a candidate for a second RSG stage.

3. Luminous Blue Variables (LBVs)

The term LBV has been rather loosely used in the astronomical literature during the past few years, so I begin with a description of the LBV/S Dor variability and the distinction with giant eruptions.

3.1. What is an LBV/S Dor variable?

An LBV or S Dor variable is distinguished by its rather unique spectroscopic and photometric variablilty. In quiescence, an LBV or S Doradus variable is a moderately evolved hot star, with a B-type supergiant or Of-type/late-WN classification. In its maximum light stage or "LBV eruption", enhanced mass loss causes its wind to become dense and opaque, with a large pseudo-photosphere at $T \sim$ 7000-8000K resembling the spectrum of an F-type supergiant. On an HR diagram the object thus appears to move toward the right. Since this alters the bolometric correction, the visual brightness increases by $\sim$ 1 to 2 magnitudes while the total luminosity remains nearly constant [15,16] or may decrease [17]. Such an event can last for several years or even decades.

There is no consensus on the origin of the LBV instability, but most explanations invoke their proximity to their Eddington limit, and include the opacity-modified Eddington limit, rotation, super-Eddington winds, or gravity-mode instabilities.

One of the distinguishing characteristics of LBV/S Dor variability is that during quiescence or minimum light they lie on the S Dor instability strip first introduced by Wolf [18], see Figure 3. The more luminous, classical LBVs above the upper luminosity boundary have very likely not been red supergiants, while those below may be post-red supergiant candidates. Thus LBVs with very different initial masses and different evolutionary histories occupy the same locus in the HR Diagram. This empirical relation remains unexplained.

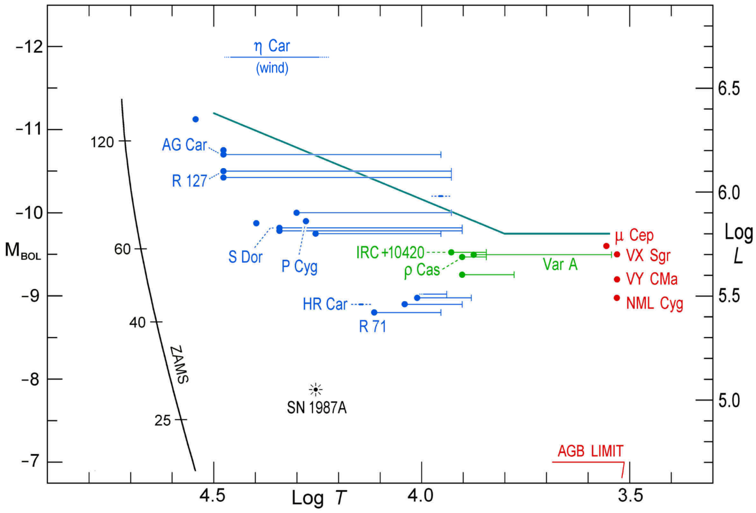

Figure 4. A schematic HR Diagram. A sample of known LBV/S Dor variables are shown in blue. The straight blue lines illustrate their apparent transits in the HRD during the LBV optically dense wind state. The dark green line is the upper luminosity boundary. Several cool (red) and warm hypergiants (green) are also shown.

3.2. The supernova impostors

In rare cases, however, the luminosity substantially increases during outburst; these have been called giant eruption LBVs [16] or "supernova impostors"[18] because they are often initially mistaken for true supernovae and receive a supernova designation. Their luminous energies often rival that of true supernovae. Historical examples include the "great eruption" of eta Car in 1843, P Cygni in 1600, SN 1961V, and V12 in NGC 2403 (SN 1954J). The distinction between giant eruptions and the more common LBV or S Dor-type variability is often overlooked in the literature. They may be related and originate from similar types of stars, perhaps in the same evolutionary stage, but the physical cause of the eruption or instability is very likely different. Certainly the energetics of the eruptions and what we observe are very different. There are numerous questions about the origin of the giant eruptions, their relation to normal LBV outbursts, and perhaps even to SNe. These eruptions are important. They may account for considerable mass loss and they indicate that some instability has been overlooked in stellar theory. *But it is important to distinguish them from the normal LBV/S Dor variability.*

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Roberta Humphreys giving her talk.