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THE CIRCUMSTELLAR ENVIRONMENTS OF THE COOL HYPERGIANTS: IMPLICATIONS FOR THE MASS LOSS MECHANISM

Roberta M. Humphreys[1]

RESUMEN

Las hipergigantes frías son las estrellas más luminosas conocidas en la parte superior del diagrama HR en el aparente rango de temperatura representado por los tipos espectrales de la A a la M. La mayoría de estas estrellas en este régimen son inestables, como lo ponen de manifiesto sus altas tasas de pérdida de masa, lavariabilidad, y en algunos casos los grandes excesos infrarrojos así como el material circunestelar expulsado. En este artículo corto, describo la complejidad del material eyectado de dos hipergigantes notables, IRC+10420 y VY CMa, y la evidencia de episodios de alta perdida de masa en sus historias recientes, aparentemente impulsadas por actividad convectiva a gran escala.

ABSTRACT

The cool hypergiants are the most luminous known stars in the upper HR Diagram in the apparent temperature range represented by the spectral types A to M. Most of these stars in this regime are unstable as evidenced by their high mass loss rates, variability, and in some cases large IR excesses and circumstellar ejecta. In this brief paper, I describe the complex circumstellar ejecta of two remarkable hypergiants IRC+10420 and VY CMa and the evidence for high mass loss episodes in their recent history apparently driven by large-scale convective activity.

Key Words: **CIRCUMSTELLAR MATTER — STARS: MASS LOSS — STARS: SUPERGIANTS**

1. WHAT IS A COOL HYPERGIANT?

A few highly unstable, very massive stars lie on or near the empirical upper luminosity boundary in the HR diagram (Figure 1). These include the Luminous Blue Variables, the cool hypergiants, and even rarer objects, all related by high mass loss phenomena, sometimes violent, which may be responsible for the existence of the upper boundary (Humphreys & Davidson 1994). In this paper, I use the term 'cool hypergiant' for the stars that lie just below this upper luminosity envelope with spectral types ranging from late A to M. The cool hypergiants very likely represent a very short-lived evolutionary stage, and are distinguished by their high mass loss rates. Many of them also show photometric and spectroscopic variability, and some have large infrared excesses, and extensive circumstellar ejecta.

The evolutionary state of most of these stars is not known. They are all post main sequence stars, but the intermediate–type or "yellow" hypergiants could be either evolving to cooler temperatures or be post-red supergiant (RSG) stars in transition to warmer temperatures. de Jager (1998) has suggested that most if not all of the intermediate temperature hypergiants are post-RSGs. In their post-RSG blueward evolution these very massive stars enter a temperature range (6000–9000 K) with increased dynamical instability, a semi-forbidden region in the HR diagram, that he called the *"yellow void"*, where high mass loss episodes occur.

To better understand the evolution of these cool, evolved stars near the upper luminosity boundary and the mass loss mechanisms that dominate the upper HR diagram, we have obtained high resolution multi-wavelength images with HST/WFPC2 of several of the most luminous known evolved cool stars – the M-type hypergiants, μ Cep (M2e Ia), S Per (M3-4e Ia), NML Cyg (M6 I), VX Sgr (M4e Ia–M9.5 I), and VY CMa (M4–M5 Ia) and the intermediate-type (F and G–type) hypergiants, IRC+10420 (A–F Ia) ρ Cas (F8p Ia), HR 8752 (G0-5 Ia) and HR 5171a (G8 Ia). The presence or lack of fossil shells, bipolar or equatorial ejecta, and other structures in their ejecta will be a record of their current and prior mass loss episodes and provide clues to their evolutionary history. These stars were selected on the basis of their infrared emission, strong molecular emission, or peculiar spectroscopic variations to give us a snapshot of different steps in their evolution across the top of the HR Diagram.

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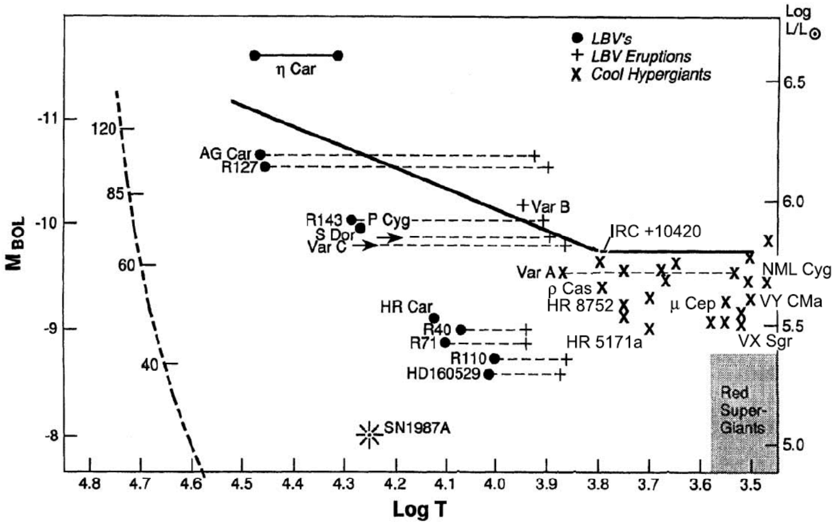

Fig. 1. A schematic HR Diagram for the most luminous stars. The empirical upper luminosity boundary is shown as a solid line, and the cool hypergiants are identified with crosses.

Our results are quickly summarized: we found no detections of circumstellar material associated with ρ Cas, HR 8752, HR 5171a and μ Cep; VX Sgr and S Per, both OH/IR sources, were marginally resolved. NML Cyg's (OH/IR source) ejecta has been shaped by its environment and IRC+10420 and VY CMa (OH/IR sources) have extensive and complex circumstellar nebulae.

In this short paper, I describe our results for NML Cyg, IRC+10420 and VY CMa and the implications for the episodic mass loss mechanism in the latter two objects.

2. NML CYG – SHAPED BY ITS ENVIRONMENT

The powerful OH/IR source NML Cyg (M6 I) is approximately 1.7 kpc from the sun and $\sim$ 100 pc from the large association Cyg OB2 in the X-ray emitting Cygnus X superbubble (Humphreys 1978; Morris & Jura 1983; Knödlseder 2003). This distance places it near the empirical upper luminosity boundary for red supergiants with a luminosity of $5 \times 10^5\ L_\odot$ ($M_{bol} \sim -9.5$) and a mass loss rate of $6.4 \times 10^{-5}\ M_\odot yr^{-1}$ (Hyland et al. 1972; Morris & Jura 1983). HST/WFPC2 images (Schuster, Humphreys, & Marengo 2006) show that NML Cyg has a very obvious but small circumstellar nebula with a peculiar asymmetric shape (Figure 2).

There are remarkable similarities between the small($\sim 0\farcs3$), asymmetric envelope that we see and the much more distant ($\sim 30''$ from the star) 21 cm ionized hydrogen (H II) contours around NML Cyg observed by Habing et al. (1982). Morris & Jura (1983) showed that the asymmetric "inverse" H II region was the result of the interaction of a spherically symmetric, expanding wind from NML Cyg and photo-ionization from plane parallel Lyman continuum photons from the luminous, hot stars in the nearby association Cyg OB2 (see Figures 1 and 2 in Morris & Jura 1983). The presence of ionized hydrogen surrounding an M supergiant like NML Cyg was somewhat of an enigma. To explain its presence, they suggested that the molecular material in the wind is photo-dissociated closer to the star so that it does not shield the atomic hydrogen from the ionizing photons (from Cyg OB2) farther out.

Our images show circumstellar material much closer to NML Cyg than the surrounding H II region and coincident with the water masers, as well as SiO masers, suggesting that we are likely imaging the molecular photo-dissociation boundaries. Schuster et al. (2006) propose that the shape of the envelope seen in the WFPC2 images is the result of the interaction between the molecular outflow from NML Cyg and the near-UV continuum flux from Cyg OB2, i.e., analogous to an "inverse Photo-Dissociation Region" (PDR). To test our hypothesis, Schuster et al modeled the shape of the photo-dissociation boundary.

Figure 2 shows the dissociation surface superimposed on the HST/WFPC2 image. It is especially interesting that the asymmetric one-sided distribution of the water masers is not only similar in extent to the reflection nebula, but also matches its convex shape. The dusty cocoon engulfing NML Cyg must

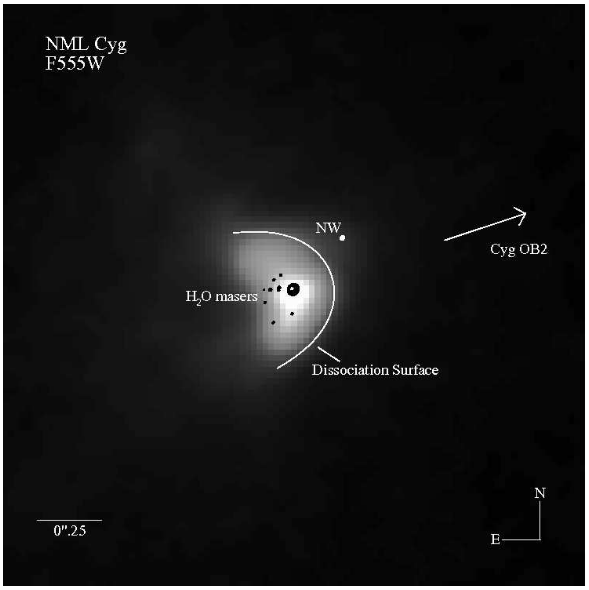

Fig. 2. The small bean-shaped asymmetric nebula surrounding the optically obscured star NML Cyg. The positions of the H_2O masers are superimposed on the image together with the dissociation surface modeled by Schuster et al. (2006) fit to the envelope of the nebula.

be the consequence of high mass loss in the RSG stage, but its envelope has most likely been shaped by its interaction with and proximity to Cyg OB2. If the outflow from NML Cyg is bipolar (Richards et al. 1998), then it appears that the molecular material SE of the star is preferentially shielded from photo-dissociation. Even without assuming bipolarity, there is more maser emission to the ESE, consistent with our model for NML Cyg's circumstellar envelope.

3. IRC+10420 – A POST–RED SUPERGIANT

IRC +10420 may be one of the most important stars in the HR diagram for understanding the final stages of massive star evolution. With its high luminosity of $L{\sim}5{\times}10^6\ L_\odot$ (Jones et al. 1993) and extraordinary mass loss rate of 3 - 6 × $10^{-4}\ M_\odot$ yr^{-1} (Knapp & Morris 1985; Oudmaijer et al. 1996; Humphreys et al. 1997), IRC+10420 is one of the few known stars that define the empirical upper luminosity boundary in the HR diagram at intermediate temperatures, between the main sequence and the red supergiant region.

Jones et al. (1993) combined multi-wavelength spectroscopy, photometry, and polarimetry to confirm a large distance of 4-6 kpc and its resulting high luminosity. With its high mass loss rate, large infrared excess and strong maser emission, they concluded that IRC +10420 is a post-red supergiant evolving back toward the blue side of the HR diagram, in an evolutionary phase analogous to the proto-planetary/post-AGB stage for lower mass stars. HST/WFPC2 images (Humphreys et al. 1997) revealed a complex circumstellar environment, with a variety of structures including condensations or knots, ray-like features, and several small, semicircular arcs or loops within 2″ of the star (Figure 3), plus one or more distant reflection shells. These features are all evidence for high mass loss episodes during the past few hundred years.

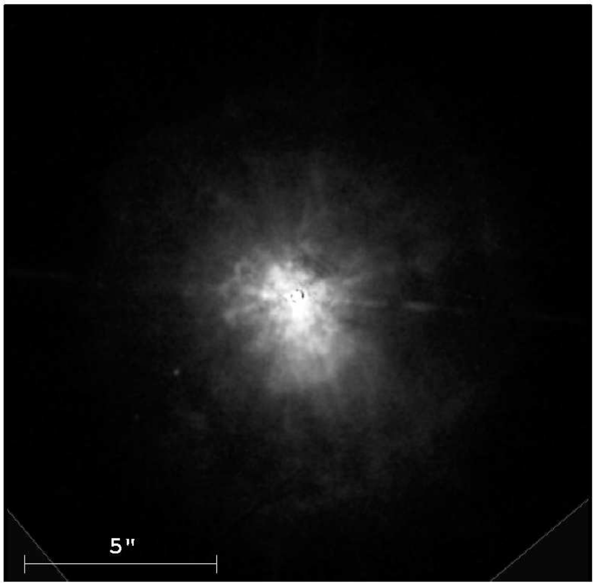

Fig. 3. A short exposure HST/WFPC2 image showing the complex inner ejecta within 2″ of the embedded star.

A few other intermediate-temperature hypergiants such as ρ Cas and HR 8752 occupy the same region in the HR diagram, but IRC +10420 is the only one with obvious circumstellar nebulosity, making it our best candidate for a star in transition from a red supergiant possibly to an S Dor-type variable (LBV), a Wolf-Rayet star, or a pre-supernova state. Moreover, its photometric history (Gottleib & Liller 1978; Jones et al. 1993) and apparent change in spectral type from late F to mid A (Jones et al. 1993; Oudmaijer et al. 1996; Oudmaijer 1998) indicate that it has changed significantly in the past century.

With this background Humphreys et al. (2002) obtained HST/STIS spatially resolved spectroscopy of IRC +10420 and its reflection nebula. Measurements of the double-peaked Hα emission profile show a uniform outflow of gas in a nearly spherical distribution, contrary to previous models with an equatorial disk or bipolar outflow. We demonstrate that at its temperature and with its high mass loss rate, the wind must be optically thick; consequently the observed variations in apparent spectral type and inferred temperature are due to changes in the wind, and not to interior evolution on short timescales.

4. VY CANIS MAJORIS – AN EXTREME RED SUPERGIANT

The extreme red supergiant and powerful infrared source and OH maser VY CMa is one of the most luminous evolved stars known. At its distance of 1.5 kpc (Herbig 1972; Lada & Reid 1978; Marvel 1997), VY CMa's luminosity is $\approx 4.3 \times 10^5 L_\odot$. Its very visible asymmetric nebula, $10''$ across, combined with its high mass loss rate of $4\times10^{-4} M_\odot yr^{-1}$ (Danchi et al. 1994), makes VY CMa a special case even among the cool hypergiants that define the upper luminosity boundary in the HR Diagram (Humphreys & Davidson 1994; de Jager 1998). VY CMa is ejecting large amounts of gas and dust at a prodigious rate, and is consequently one of our most important stars for understanding the high mass loss episodes near the end of massive star evolution.

Multi-wavelength HST/WFPC2 images of VY CMa (Smith et al. 2001) revealed a complex circumstellar environment dominated by the prominent nebulous arc to the northwest, which is also visible in groundbased data, two bright filamentary arcs to the southwest, plus relatively bright clumps of dusty knots near the star, all of which are evidence for multiple and asymmetric mass loss episodes (Figure 4). The apparent random orientations of the arcs suggested that they were produced by localized ejections, not necessarily aligned with an axis of symmetry or its equator. Therefore, we speculated that the arcs may be expanding loops caused by localized activity on the star's ill-defined surface.

To learn more about the morphology, kinematics and origin of VY CMa's complex ejecta, Humphreys et al. (2005) obtained long-slit spectra with HIRES on the Keck 1 telescope to map the emission and absorption lines in the nebula. The four slits were placed across several structures in the nebula including the NW arc, the two outer filamentary arcs and clumps of bright knots. The Doppler motions of the reflected absorption lines and extremely strong K I emission line revealed a complex pattern of velocities in the ejecta. We found a strong velocity gradient across the NW arc which is expanding at ~ 50 km s^{-1} with respect to the embedded star, and is "kinematically distinct" from the surrounding nebulosity. It was apparently ejected $\approx$ 400-500 yrs ago while the two outer filamentary arcs were ejected in separate events possibly up to 800 yrs ago. Small arcs and knots closer to the star were ejected more recently.

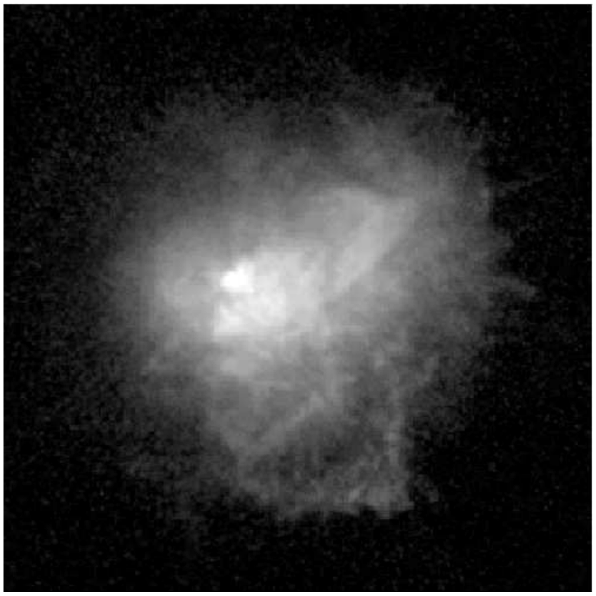

Fig. 4. The HST/WFPC2 image of VY CMa showing the multiple arcs and knots in its circumstellar ejecta.

We (Humphreys et al. 2007) have since obtained second epoch HST/WFPC2 images to measure the transverse motions which when combined with the radial motions provide a complete picture of the kinematics of the ejecta including the total space motions and directions of the outflows. Our results show that 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. We conclude that the morphology and kinematics of the arcs and knots are consistent with a history of mass ejections not aligned with any presumed axis of symmetry.

5. THE MASS LOSS MECHANISM – THE ROLE OF STELLAR ACTIVITY

The origin of the mass loss and variability observed for the majority of normal RSG's and the irregular and long-period variables is most likely pulsational instability. Indeed, pulsational instability appears to be the cause of the small shell ejection events in the hypergiant star ρ Cas (Lobel et al. 2003).

In contrast, the numerous arc-like structures, knots, and filaments in the circumstellar ejecta of VY CMa and IRC+10420 are evidence for multiple, asymmetric mass loss events at different times and apparently by localized processes from different regions on the star. This activity could be attributed to either non-radial pulastions or to magnetic/convective regions and events analogous to solar activity, that is large "starspots". Large and variable starspots and accompanying outflows have been observed on the less luminous, less massive RSG α Ori (see numerous papers by Dupree and collaborators).

Measurements of the circular polarization of the H_2O (Vlemmings et al. 2002, 2004) and SiO masers (Barvainis et al. 1987; Kemball & Diamond 1997) in VY CMa and the Zeeman spliting of the OH emission (Szymczak & Cohen 1997; Masheder et al. 1999) confirm the existence of a magnetic field throughout its ejecta. The results also imply magnetic fields of more than 10^4G at the star's surface assuming the r^{-2} dependence of a solar-type magnetic field that would be associated with large starspots, convective activity and mass ejections. Using surface photometry of its optical and infrared images, Smith et al. (2001) estimated the total mass in VY CMa's circumstellar nebula to be 0.2 to $0.4 M_\odot$ with a mean mass loss rate of $3 \times 10^{-4} M_\odot$ yr^{-1} over the past 1000 yrs. In a similar fashion, the mass of the NW arc was estimated to be at least $\sim 3 \times 10^{-3} M_\odot$. Based on those results, Humphreys et al. (2007) estimate that the total mass in the prominent arcs and the clumps of bright knots may be $1.5 \times 10^{-2} M_\odot$ or more, $\sim$ 10% of the total mass in the ejecta. This estimate does not take into account the numerous small filaments and knots visible throughout the nebula or similar massive flows not visible through the optically thick nebula. With a dynamical time scale of 3 yrs (Smith et al. 2001), the short-term mass loss rate associated with the NW arc and similar features, is $\geq 10^{-3} M_\odot$ yr^{-1}, several times the average mass loss rate.

In the "yellow" hypergiant IRC+10420 the outermost reflecton arcs at $\approx 5''$ were ejected about 3000 years ago, probably when the star was still red supergiant. The numerous arcs, knots, and jet-like structures indicate localized ejection events in seemingly random directions, analogous to VY CMa although the morphology is not identical. Located within $2''$ these features represent several high mass loss episodes within the last 600 yrs. shedding about 1 $M_\odot$ with a mass loss rate $\sim 10^{-3}$ $M_\odot$ yr^{-1}. These events very likely occurred after the star had ceased to be a cooler RSG, although the timescales for post red supergiant evolution are uncertain. Its high mass loss period may have recently ended, about 60 - 90 yrs ago (Blöcker et al. 2001).

The case for convection and turbulence may be strongest among the RSG's, but it appears that convective/magnetic activity may also occur in the post-RSG stage. This should not be too surprising given the dynamical instability of IRC+10420's surface. Strong magnetic fields of the order of 1 mG have been reported in the OH maser regions (Nedoluha & Bowers 1992) at about 7000 AU implying surface fields of several thousand G, similar to VY CMa.

We now observe increasing evidence among the evolved massive stars (η Car, LBVs, and the cool hypergiants) for episodic mass loss. In the cool hypergiants (IRC+10420, VY CMa, VX Sgr, S Per, NML Cyg), the high mass loss episodes are apparently driven by large-scale convection and magnetic fields.

6. THE SUPERNOVA IMPOSTORS

I was somewhat surprised that there was no paper on the program specifically about LBV's, although I'm sure they will be discussed during this meeting. So I thought I'd just briefly mention a subgroup of the LBV's that are increasingly known as "supernova impostors" and are obviously relevant to the subject of this meeting.

A small subset of the S Dor variable or LBVs that have been variously called "giant eruption" LBVs or "η Carinae" variables (Humphreys & Davidson 1994; Humphreys, Davidson, & Smith 1999) or "η Car analogs" (Van Dyk 2005) experience eruptions during which their total luminosities increase significantly and the star survives. Given the very high luminosities reached during these giant eruptions and because several members of this group have been called supernovae at various times, we sometimes call them "supernova impostors", a somwhat catchier name.

η Car is the best known example. Other members of this small group include P Cygni in the 17th century, SN 1961v in NGC 1058, V12 in NGC 2403(SN 1954j, and V1 in NGC 2363 which has recently been "caught in the act" (Drissen et al. 1997, 2001; Petit et al. 2006). The "pistol" star near the galactic center (Figer et al. 1998; Najarro 2005) may be a similar object.

Another reason to call these stars "supernova impostors" is because several candidates, most of which are normal LBVs, have been discovered in the recent supernovae surveys among the Type IIn's. Several papers and the discussion in the "The Fate of the Most Massive Stars" (ASP Conference Series, Volumen 332, 2005) provide a good background reference on these objects as more of them continue to be found in the SNe surveys.

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