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The Evolutionary State of the Cool Hypergiants – Episodic Mass Loss, Convective Activity and Magnetic Fields

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Abstract. The evolved cool stars near the empirical upper luminosity boundary in the HR Diagram all show evidence for considerable instability perhaps due to their proximity to this stability limit and/or their evolutionary state. Recent high resolution imaging and spectroscopy of several of these stars have revealed a subset characterized by complex ejecta and evidence for episodic mass loss driven by convective activity and magnetic fields. This group includes famous stars such as the red supergiants VY CMa, NML Cyg and the post RSG IRC +10420. I will review the observational evidence and discuss the implications for the final stages of these evolved stars, their mass loss mechanism, and evolutionary state.

Keywords. stars: mass loss – stars: magnetic fields – stars: evolution

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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. 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 1979, 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–type 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

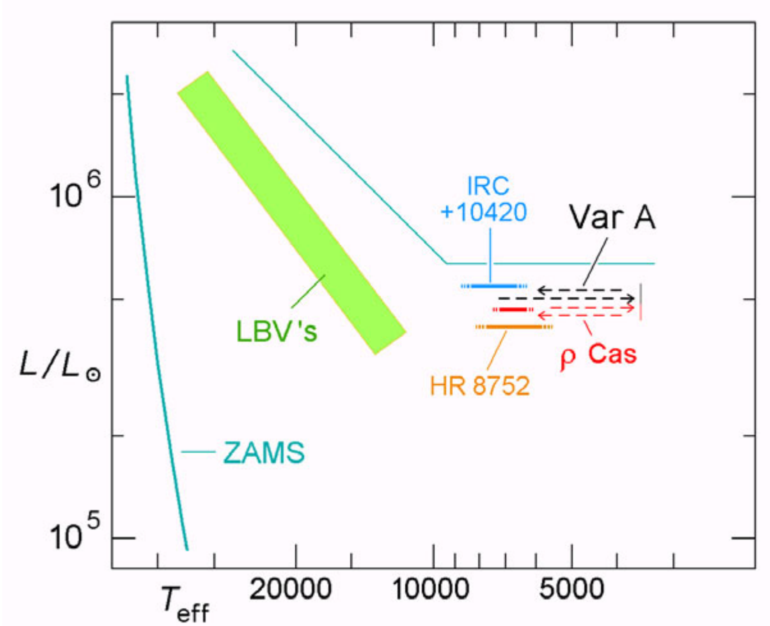

Figure 1. A schematic HR Diagram showing the positions of the intermediate – type hypergiants and their apparent shifts in temperature due to changes in their wind and formation of an optically thick cooler wind.

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.

Our results are quickly summarized: we found no detections of visible 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.

2. The Yellow or Intermediate–Type Hypergiants

Although ρ Cas is famous for its shell ejection episodes in 1945-47, 1985-87, and 2002, we found no evidence for visible CS ejecta in its HST images and the near-infrared adaptive optics images were also negative (Schuster *et al.* 2008). During these events, it develops TiO bands accompanied by a high but temporary mass loss rate ($\approx 10^{-2}$M$_\odot$ yr^{-1}) due to the formation of an optically thick wind. It quickly returns to its normal F supergiant type spectrum. Prior to this recent episode, its apparent temperature had been slowly increasing (see Figure 1), but after the event it returned to its former lower temperature and F-type spectrum. The star's photometric variability was indicative of pulsational instability (Lobel *et al.* 2003). Thus its apparent shift on the HR Diagram was not due to evolution but to changes its wind or envelope.

Variable A in M33, while not one of our imaging targets, experienced a similar high mass loss episode with the formation of a much cooler optically thick wind or false-photosphere like ρ Cas, but its event lasted $\approx$ 45 years! Var A was one of the original

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Hubble- Sandage variables and one of the visually brightest stars in M33, when in 1950 it rapidly declined 3 mags. or more becoming very red. Its spectrum in 1985-86 was that of an M supergiant and it had a strong IR excess (Humphreys *et al.* 1987). In 2004-05 its spectrum had returned to its prior warmer F-type and it had gotten bluer (Humphreys *et al.* 2006). Like ρ Cas its apparent transits on the HRD are not due to interior evolution, but to changes its wind or photosphere.

2.1. *The Post–Red Supergiant IRC+10420*

IRC +10420 may be one of the most important stars in the HR diagram for understanding the final stages of massive star evolution. 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 and large infrared excess, they concluded that IRC +10420 is a post–red supergiant evolving back toward the blue side of the HR diagram, in an evolutionary phase perhaps analogous to the proto-planetary/post-AGB stage for lower mass stars. IRC+10420 is also the warmest maser source known and in the past 20 years or so its apparent spectral type has gone from late F-type to a mid-A (Oudmaijer *et al.* 1996, Oudmaijer 1998).

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, 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.

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 indicate that it has changed significantly in the past century. Humphreys *et al.* (2002) obtained HST/STIS spatially resolved spectroscopy of IRC +10420 and its reflection nebula and demonstrated that at its temperature and with its high mass loss rate, the wind must be optically thick. Consequently, like ρ Cas and Var A, its observed variations in apparent spectral type and inferred temperature are due to changes in the wind, and not to interior evolution on such short timescales.

3. The Red Supergiants

Our WFPC2 images revealed visible CS ejecta around all of our M-type supergiant candidates except for the very luminous μ Cep, although near-IR adaptive optic imaging resolved its dust shell at the expected distance (Schuster *et al.* 2008). All of the stars with detectable ejecta are known supergiant OH/IR stars and are strong sources of maser emission.

3.1. *NML Cyg – Interacting with Its Environment*

The HST/WFPC2 images of the powerful OH/IR maser NML Cyg (M6 I) shows an optically obscured star embedded in a small asymmetric bean-shaped nebula (Schuster, Humphreys & Marengo 2006). This small CS nebula is remarkably similar in shape to the 21cm ionized hydrogen (H II) contours $\sim$ 30" from the star. The presence of ionized hydrogen surrounding an M supergiant like NML Cyg was somewhat of an enigma. Morris & Jura (1983) showed that the asymmetric "inverse" H II region was the result of

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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). 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.

Our images show circumstellar material much closer to NML Cyg than the surrounding H II region and coincident with the water masers and SiO masers, suggesting that we are likely imaging the molecular photo-dissociation boundaries. Schuster *et al.* (2006) show that the shape of the envelope seen in the WFPC2 images can be modeled as 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). The water masers show a one-sided asymmetric distribution similar in extent to the reflection nebula, that also matches its convex shape (see Figure 6 in Schuster at al 2006). The dusty cocoon engulfing NML Cyg must 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.* 1996), 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.

3.2. *The Extreme Red Supergiant VY CMa*

The extreme red supergiant and 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, 10" across, 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. 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 ground-based 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 2). 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. We therefore speculated that the arcs may be expanding loops caused by localized activity on the star's ill-defined surface.

We subsequently obtained obtained second epoch HST/WFPC2 images to measure the transverse motions which when combined with the Doppler velocities (Humphreys *et al.* 2005) provide a complete picture of the kinematics of the ejecta including the total space motions and directions of the outflows (Humphreys, Helton & Jones 2007). 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. Independent polarimetry (Jones, Humphreys & Helton 2007) confirms the line of sight orientation of the primary features and together with the kinematics lets us determine the *three-dimensional morphology of the ejecta.*

Figure 2. The HST/WFPC2 image of VY CMa showing the multiple arcs and knots in its circumstellar ejecta.

4. Episodic Mass Loss, Convective Activity and Magnetic Fields

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 pulsations or to magnetic/convective regions and events analogous to solar activity, that is large "starspots". The distinction may be vague for a red supergiant where the convective cells are expected to be comparable to the stellar radius in size (Schwarzschild 1975); although, nonradial pulsations would not be expected to produce the narrow arcs and loops observed in VY CMa. Starspots and large "asymmetries" have now been observed on several stars including red giants, AGB stars and supergiants.

Vlemmings *et al.* (2002, 2005) have measured the magnetic field strength from the circular polarization of H_2O masers in the ejecta of AGB stars and several evolved supergiants including the strong OH/IR sources VY CMa, VX Sgr, NML Cyg, and S Per. They show that the H_2O masers around VX Sgr can be fit by a dipole magnetic field (Vlemmings *et al.* 2005). Their analysis supports the Zeeman interpretation of the circular polarization of the SiO masers (Barvainis et al 1987; Kemball & Diamond 1997) only a few AU from the surface of these stars. Together with Zeeman splitting of the OH emission far out in the wind at a few thousand AU (Szymczak & Cohen 1997; Masheder et al 1999), these measurements confirm the presence of a magnetic field throughout the ejecta of these objects. The results for VY CMa imply magnetic fields of $\sim$ 8000G at the star's surface. Similarly, for IRC+10420, the circular polarization of the OH masers (Nedoluha & Bowers 1992) imply fields of $\sim$ 3000G at the surface. This may be high for a global field but perhaps not for large convective cells.

5. The Evolutionary State?

In published papers and at previous IAU symposia I have suggested that these RSGs with the visible CS ejecta represent a short-lived, high mass loss phase. That is very likely

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the case but we have to take a closer look at these stars and ask why. de Jager (1998) has suggested that the "yellow" hypergiants are all post-RSGs. IRC+10420 fits this model very well, but ρ Cas with its well documented mass loss episodes plus the similar high luminosity stars, HR5171a and HR8752†, show no visible CS ejecta. It is possible that they are not post-RSGs but are still evolving from the blue to the red supergiant region, or alternatively that they have only recently entered this region of dynamical instability.

It must be emphasized that all of these objects are evolved (post-MS) stars of high initial mass and high luminosity. Proximity to the Humphreys-Davidson limit however, does not appear to be the explanation for the presence of extensive CS ejecta; ρ Cas for example is quite close (Figure 1), while S Per is significantly fainter.

So what do these stars with the CS ejecta have in common – VY CMa, IRC+10420, NML Cyg, VX Sgr and S Per? They are all supergiant OH/IR stars with strong maser emission. Most OH/IR sources are AGB stars. Only a few are above the AGB limit and therefore recognized as supergiants or massive stars. I am therefore suggesting that these hypergiant-OH/IR stars have been on a blue loop in the HRD and are now in the RSG stage for the second time, analogous to the AGB stars at lower mass. IRC+10420 could indeed be a star evolving back to the blue for the second time similar to the post-AGB stars. If so, these stars must be very close to the end of their lives.

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† HR8752 has a nearby hot companion star which may prevent the formation of a dusty nebula.

Discussion

OWOCKI: How are the magnetic fields measured?

HUMPHREYS: The magnetic fields were measured from the circular polarization of the H_2O masers, the SiO masers and the Zeeman splitting of the OH masers. The references are given in the paper.

HILLIER: What is the argument that indicates ρ Cas had a shell ejection rather than a expansion of the outer envelope?

HUMPHREYS: "Shell episode" or "ejection" is the terminology used in the literature for the ρ Cas events. Modern observations show that these are really the formation of a cool optically thick wind or false photosphere similar to what is observed in the classical LBVs but for cooler stars.

MAEDER: You are associating these episodic ejections with convection. Could it also be due to pulsation?

HUMPHREYS: Regular pulsation cannot explain these spatially separate episodic ejections. The distinction between large convective cells and non-radial pulsation may be vague on these size scales. But non-radial pulsation would not produce the narrow arcs and loops seen in the ejecta of VY CMa. These visible structures, while resembling prominences, thousands of AU from the star, are not connected to the chromosphere, but are the giant loops or bubbles swept up by large gas outflows extending over several arc secs in the ejecta as revealed by the spectroscopy. They most closely resemble coronal mass ejections.

KUDRITZKI: Steffen and Freytag have done 3D pulsational simulations of α Orionis and show pronounced spot features and deviations from symmetry. Could this explain your observations?

HUMPHREYS: They may be able to simulate a pulsation that produces asymmetries. But remember these are cool stars with large convective envelopes and the magnetic fields are now observed in the ejecta of these stars and several AGBs. In the case of VX Sgr, a dipole magnetic field fits the observations. The magnetic field had to get there somehow.

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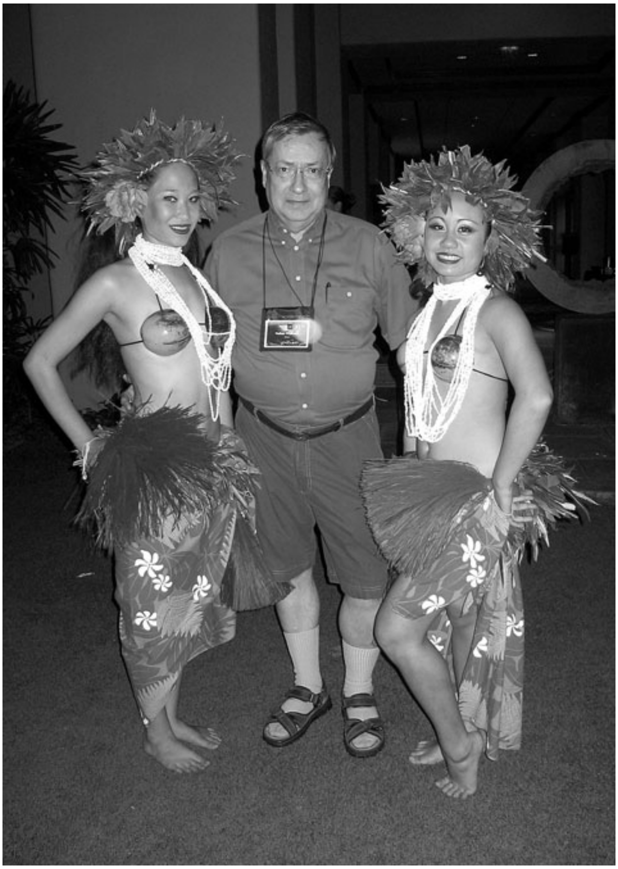

Nolan Walborn and friends.

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