The Cool Hypergiants (A to M): Their Physical Characteristics and Role in Explaining the Upper Luminosity Limit in the HR Diagram

ABSTRACT

High mass loss rates and evidence for instabilities are observed in the photospheres of most of the stars, both hot and cool, that lie on or near the observed upper luminosity boundary in the HR diagram. In this Workshop we are emphasizing the instabilities in the luminous cool stars, defined as those with spectral types A to M. Consequently in this introductory review, I will briefly look at all of the unstable luminous stars across the top of the HR diagram, and then concentrate on the observations of individual cool hypergiants and what they imply about the causes and consequences of their instabilities.

HOT AND COOL STARS ALONG THE UPPER LUMINOSITY LIMIT

The observed upper luminosity limit (Humphreys and Davidson 1979, 1984) is defined by the distribution of the most luminous stars (highly variable stars and known binaries were not included) in Local Group galaxies, primarily the Milky Way and the Magellanic Clouds. The most luminous hot stars reveal an upper envelope of declining luminosity with decreasing temperature which for the cooler stars, temperatures less than 8000-10000 K, becomes an upper boundary of essentially constant luminosity. The temperature dependent boundary for the hot stars suggests that it is mass dependent in contrast to the nearly temperature-independent upper limit to the luminosities of the cool hypergiants. This observed boundary near $M_{Bol} \simeq -9.5$ mag corresponds to an initial mass near 40 $M_{\odot}$. The characteristics of some of the most luminous stars provide empirical evidence that the observed luminosity boundary is due to the instability of these very massive evolved stars.

a. Luminous Blue Variables

The luminous blue variables (LBV's) are a small group of high-luminosity, unstable, hot supergiants whose behavior provides important insight into understanding the luminosity/stability limit in the HR diagram. The LBV's include such well-known stars as η Carinae and P Cygni in our Galaxy, S Doradus in the Large Magellanic Cloud, and stars known as the Hubble-Sandage variables in the spiral galaxies M31 and M33. Their most distinguishing characteristic is the occurrence of irregular eruptions or ejections that result in a greatly enhanced mass outflow (10^{-5}-10^{-4} $M_{\odot}$ yr^{-1}), leading to the formation of a pseudophotosphere when the star is at maximum light at visual wavelengths. At this stage, the slowly expanding (100-200 km s^{-1}) envelope is cool (8000-9000 K) and dense ($N \simeq 10^{11}$ cm^{-3}), and the star resembles a very luminous A-type supergiant. At its minimum light (in the visual), or the quiescent stage, the LBV has a much higher photospheric temperature (20,000-25,000 K), and resembles an OB supergiant, but with prominent emission lines of hydrogen, He I, and permitted and forbidden FeII in its spectrum. At visual minimum the mass loss rate of an LBV is lower by a factor of 10-100. During the variations in visual light, the total luminosity of the LBV remains constant. The visual light variations are caused by the apparent shift in the star's energy distribution driven by its instability. The schematic HR diagram in Fig. 1 shows the location of the well-studied LBV's at visual minimum and maximum. Notice that at visual maximum they all have about the same temperature, near 8000 K. In addition to their light variations, many of the LBV's are surrounded by ejected material from previous eruptions. Analysis of this circumstellar material shows that it contains processed material such as nitrogen and helium from the star's interior. This shows that the LBV's are evolved, post-hydrogen-burning stars.

The most likely cause of the instability in the LBVs and of the luminosity boundary for hot stars is radiation pressure. However, other processes, such as interior evolution, or hydrodynamic effects, such as atmospheric turbulence, may drive the star to the boundary between radiation pressure and gravity, the Eddington limit. But the classical Eddington limit due to electron scattering is independent of temperature, unlike the observed luminosity boundary for hot stars. However, as the temperature of the stellar photosphere decreases, the opacity increases, reducing the Eddington luminosity. Thus an instability related to this modified Eddington limit may be responsible for the upper luminosity boundary.

b. The Cool Hypergiants

The very luminous F, G, K and M stars that define the upper luminosity boundary for the cool stars (see Figure 1) all show evidence of instability including light and spectral variability, high mass loss plus extensive circumstellar dust around many. The characteristics of these stars provide an overview of the phenomena to be discussed at this meeting.

The coolest hypergiants, the most luminous M supergiants, reveal a range of characteristics, from relatively normal stars such as μ Cep with the 10μ circumstellar dust feature to the OH/IR supergiants. The OH/IR supergiants are likely the most evolved M

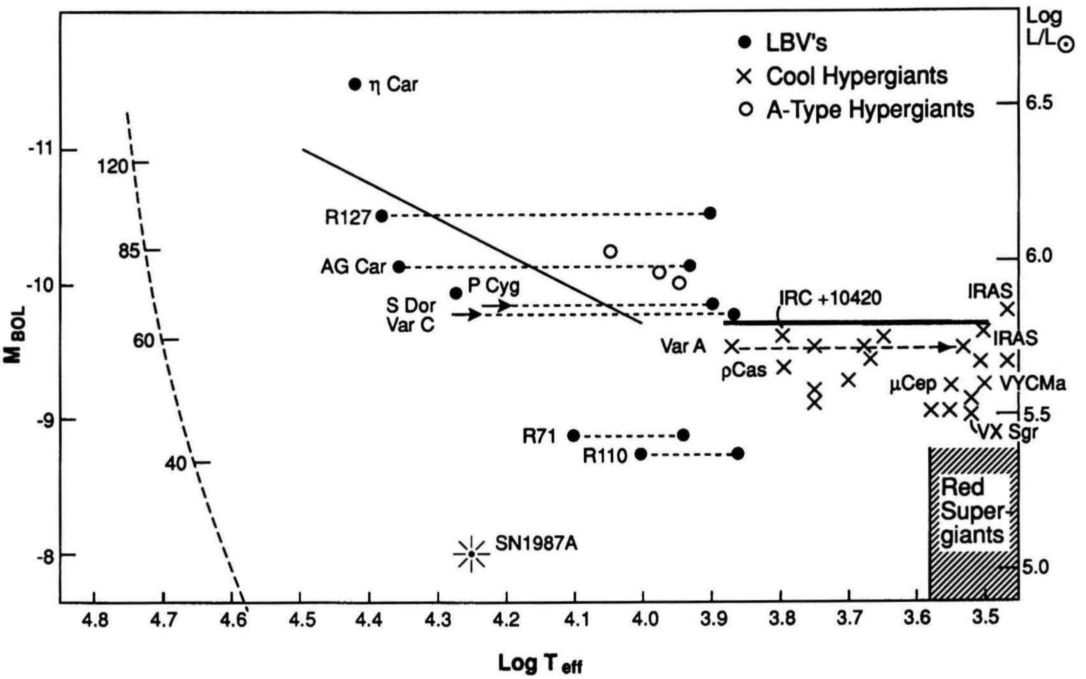

Figure 1. A schematic HR diagram showing the location of the LBV's, the cool hypergiants, and the very luminous A-type hypergiants.

supergiants (see Jones et al. 1983); those that have lost sufficient mass that their dust shells have become optically thick. The mass loss rate from the OH/IR supergiants may be extremely high, 10^{-4} to 10^{-3} $M_\odot$/yr. A few are visually bright and well known like VY CMa (M3-5eIa) and VX Sgr (M4-8eI) but most are obscured by their own circumstellar dust. The two highly obscured, highly luminous late-type stars in the LMC (Elias, Frogel and Schwering 1986) discovered by IRAS presumably belong to this group, and OH emission has been detected from one (Wood et al. 1986).

The most recent addition to the luminous and peculiar red stars is the new variable reported in M31 (Rich et al. 1989) that reached $M_{Bol} \simeq -9.8$ mag and then rapidly faded three bolometric magnitudes in 100 days. Mould et al. (1990) have suggested it is an unusual type of nova but a preliminary light curve by Sharov (1990) shows that it was also bright in 1968 and had a slow rise to maximum over several 100 days, unlike a nova. Its behavior is more reminiscent of some of the luminous irregular and semi-regular variables like VX Sgr.

Many of the intermediate-type hypergiants not only have high mass loss rates but also exhibit shell ejections. ρ Cas (F8Ia) is especially well known for its shell episode (1946-47) in which it decreased by 1.5 mag and had the spectrum of an M star. HR 8752 (G0-G5Ia$^+$) one of the most luminous known hypergiants, has shown considerable spectroscopic variation usually attributed to shell ejection (see Piters et al. 1988, Smolinski et al. 1989, Lambert et al. 1981). Curiously HR 8752 does not have any significant IR excess (at 10μ) due to circumstellar dust that is observed around many very luminous F, G and K type supergiants. ρ Cas also had no 10μ excess radiation but based on the IRAS observations, Jura and Kleinmann (1990) concluded that ρ Cas did form dust sometime between 1973 and 1983 probably as a consequence of its 1946 outburst. HR 5171A also one of the most luminous cool supergiants, has one of the largest 10μ silicate features observed in late-type supergiants. This star is especially interesting because it has been getting fainter and redder since at least 1953 which suggests that the amount of dust and circumstellar obscuration may be increasing (see paper by van Genderen this volume).

Variable A in M33 and IRC+10420 are of special interest because their characteristics, exceptional even for cool hypergiants, may provide clues to their eventual fate.

Variable A in M33 is perhaps the most enigmatic of all of the cool hypergiants (Humphreys et al. 1988). It was one of the original Hubble-Sandage variables but its behavior is bizarre even for them. In 1950 it was one of the visibly brightest stars in M33, with the spectrum of a very luminous F supergiant. It then rapidly declined in brightness by 3.5 mag becoming faint and red after slowly increasing in brightness during the previous 50 years. It is still faint and red and has the spectrum of an M supergiant not an emission-line hot star like other H-S variables. It also has a large infrared excess and is today as bright as 10μ as it was at its visual maximum in 1950. Variable A is a very luminous (M_{Bol} ≃ -9.5 mag), highly unstable ($2x10^{-4}$ $M_{\odot}$/yr) star. Its present spectrum is probably produced in an expanded pseudo-photosphere and is shedding its mass in a high-density, low-velocity wind. It is especially, interesting that on the HR diagram, Variable A lies at a very critical point, near the observed turnover in the upper luminosity boundary.

IRC+10420 has the largest IR excess observed among the cool hypergiants (Humphreys et al. 1973). It has the spectrum of a very high luminosity F supergiant and it is also one of the warmest known OH/IR sources (Giguere et al. 1976). Our recent spectra (see Humphreys, Jones, Venn and Zickgraf, this volume) show that there is most likely an equatorial disk around the star probably where the circumstellar dust is concentrated and the OH emission originates, plus possibly a more spherically distributed mass outflow or wind. One of the most interesting observations is the recent finding (Lewis et al. 1986) that the 1665 MHz OH feature is weakening while the 1612 MHz feature is growing. This is what we would expect if the dust shell were dissipating. IRC+10420 also brightened by about a magnitude from 1930 to 1970 (Gottleib and Liller 1978). If this trend continues a plausible model for IRC+10420 will be as a post M supergiant OH/IR star blowing off its cocoon of dust and gas as it evolves to the left to warmer temperatures on the HR diagram. This interpretation depends, however, on its luminosity. In our poster we show that IRC+10420 is most likely between 4 and 6 kpc from the Sun with a resulting M_{Bol} of -9.2 to -10 mag. Its luminosity is sufficiently high that it might be considered related to the LBV's in some way - very slow LBV? - especially sinced its photospheric temperature (inferred from its spectrum) is close to the temperature reached by the LBV's at visual maximum. It also might represent the final stage, i.e., lowest temperature, achieved by the A-type hypergiants right before they become full-fledged LBV's; stars like Cyg OB2 #12 in our galaxy, HD33579 in the LMC and B324 in M33.

These extremely luminous A-type stars are the visually brightest stars in their respective galaxies. They have bolometric luminosities between -10 and -10.5 mag and depending on how one wants to define (or draw) the upper luminosity boundary for the hotter stars one can say that they are either just above it or that they define its cool limit. Nevertheless these stars must be approaching the limit to their stability. HD33579 and #12 both have high mass loss rates and in a recent preprint Massey and Thompson (1991) suggest that Cyg OB2 #12 may be an incipient LBV largely because of light variations up to ∿.5 mag and small spectral variations.

Thus there are many very luminous, highly unstable stars all along the upper luminosity boundary in the HR diagram with very high mass loss. These stars will shed many solar masses in their lifetimes, sufficient to determine their evolution.

EVOLUTIONARY CONSIDERATIONS

Given their observed physical characteristics, high mass loss, the presence of CNO-processed material in their ejecta and atmospheres and their close association with the Of/WN9 stars, there is little doubt that after shedding sufficient mass, the LBV's evolve into the late WN-type stars. Thus for stars with initial masses >40 $M_{\odot}$, a highly unstable phase as an LBV followed by the WR stage is the most likely scenario for their post main sequence evolution.

But what is the eventual fate of the cool hypergiants, those stars near the luminosity-limit with initial masses close to 40 $M_{\odot}$? They are losing mass at very high rates, sufficient to produce optically thick dust shells like NML Cyg and the IRAS sources in the LMC and over their lifetimes to shed most of their outer envelopes. Among the seven known M supergiants in our galaxy between M_{Bol} = -9 to -9.5m, three are OH/IR sources. Thus it seems reasonable that most of these stars pass through an OH/IR stage.

Using the estimated lifetime (∿30000 yrs) for the supergiant OH/IR stage from Humphreys (1991) combined with the observed mass loss rates for the OH/IR stage plus average mass loss rates for the luminous red supergiants from the compilation by de Jager et al. (1988) and the lifetimes in various stages from the models by Maeder and Meynet (1988), I have estimated the amount of mass lost as an evolved supergiant for stars of three different masses 40, 25 and 20 $M_{\odot}$. The numbers are summarized in Table 1 in Humphreys (1991).

By the time the 40 $M_{\odot}$ star has passed through the region of the cool hypergiants for the second time (on a 'blue loop' back to warmer temperatures) it will have lost half of its initial mass. From the tables in Maeder and Meynet (1988) the relative surface abundance of hydrogen for a star with ∿20 $M_{\odot}$ remaining will be down to ∿.2. It will also be close to the onset of carbon fusion and the star could be well on its way to becoming a WR star. This is not to say that all of the cool hypergiants will evolve to WR stars. We have no means of determining if an intermediate type hypergiant is evolving to cooler or warmer temperatures. (Based on the models, the lifetimes of the two crossings are comparable.) Although IRC+10420 may be a good candidate for a cool hypergiant in transition from a red supergiant to a WR star, analogous to less massive stars which become the central stars of planetary nebulae.

The evolutionary scenario for evolved stars of somewhat lower mass (15-30 $M_{\odot}$) is also uncertain. We know that the progenitors of many Type II supernovae are most likely red supergiants because they must have very extended envelopes (Woosley and Weaver 1986). SN1987A and its progenitor also showed us that some red supergiants in this lower mass range evolve back to the blue and explode as supernovae as a hot, more compact supergiant. Do some evolved supergiants at these lower masses also reach the WR stage before becoming supernovae? Assuming that these stars also pass through an OH/IR stage as red supergiants, they still do not lose sufficient mass to shed their hydrogen envelopes. By the time stars of 20 and 25 $M_\odot$ are down to 13 and 12 $M_\odot$ respectively, their hydrogen surface abundances would still be $\sim$.4 (Maeder and Meynet 1988) far from the bare hydrogen-deficient core of the WR star. An additional high mass loss phase would still be required. The two low luminosity, relatively cool LBV's in the LMC, R71 and R110 might qualify as post RSG's for stars near the 30 $M_\odot$ range and would be an additional stage where high mass loss could occur. But what would be the cause of the instability at this stage?

PHYSICAL CAUSE OF THE INSTABILITY

The upper limit to stellar luminosities is usually assumed to be set by the balance between the acceleration due to gravity and the radiation pressure gradient a la Eddington. However, the observed luminosity boundary is composed of two components - the temperature-dependent boundary for hot stars and its turnover at the cool star upper limit. The classical Eddington limit due to electron scattering does not show the dependence on temperature for the hot stars. However, as the temperature decreases below 30000 K the opacity increases due to hydrogen and FeII. A modified or opacity-dependent Eddington limit which decreases with temperature has been proposed and discussed by several investigators (Humphreys and Davidson 1984, Appenzeller 1986, Lamers 1986, Davidson 1987, Lamers and Fitzpatrick 1988). The opacities reach a maximum and the Eddington luminosity a minimum near 10000 K. The modified Eddington limit will then turn up again in the 8000-10000 K temperature range in agreement with the observed turnover in the luminosity/stability limit. Stars below the corresponding critical mass could then evolve to the red supergiant region. The unstable cool hypergiants could then be those stars just slipping under the Eddington limit.

But the situation may be more complicated. First attempts to calculate the location of the modified Eddington limit on the HR diagram have not been entirely successful (Lamers and Fitzpatrick 1988). The F, G, K and M hypergiants in our galaxy and other local group galaxies define the observed upper luminosity limit for the cooler stars and these stars are all highly unstable. De Jager (1980, 1984), has suggested that the instability in these stars is produced by a turbulent pressure gradient due to the dissipation of mechanical energy. In a series of papers, he and his collaborators have measured supersonic microturbulent motions in the atmospheres of many of these stars which supports his suggestion.

If this is correct, then in the upper HR diagram we may be observing the merging or intersection of two (or more) effects: 1) the temperature-dependent Eddington limit (radiation pressure) which dominates in the hot stars, and 2) the turbulent pressure gradient which may provide a cap to the luminosities of the cool hypergiants independent of the Eddington limit. This will have important consequences. The modified Eddington limit depends on the opacity and therefore the metallicity. In lower metallicity systems the opacities will be lower and the corresponding Eddington luminosity will be higher, and the reverse will be true at higher metallicity. Thus we should observe some variation in the upper luminosity limit for the cool hypergiants if it is entirely due to the modified Eddington limit. However, we do not for the cool supergiants in Local Group galaxies; although, only three galaxies, Milky Way, LMC and SMC, are well studied for this purpose. Thus the turbulent pressure gradient may be an important factor in limiting the upper luminosities of the most luminous cool stars.

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