

Two Decades of Hypergiant Research

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Abstract. This article is a brief review of the research by Dr. C. de Jager and co-workers over the past twenty years into the physics of hypergiant atmospheres. Various important results on the microturbulence, mass-loss, circumstellar environment, atmospheric velocity fields, and the Yellow Evolutionary Void of these enigmatic stars are summarized. Aspects of recent developments and future work are also communicated.

1. Introduction

In 1980 Prof. Cornelis de Jager at the University of Utrecht published a book entitled *The Brightest Stars*. It followed years of scientific research into the question of why there are no stars brighter than a certain upper limit. In other words, what mechanism(s) determine(s) the upper limit of stellar atmospheric stability? His monograph (de Jager 1980) is a compilation which addressed nearly every aspect of massive star research, and which has formed the basis of fundamental progress about these questions during the past two decades. This ‘festschrift’ reviews some of the (partial) answers which have been proposed in the course of time by Dr. de Jager and many co-workers, however without attempting to be complete in all the scientific or chronological details. We also highlight the most important recent developments, based on a limited number of selected references to their work, which will enthuse the reader with this remarkable subject in astrophysics.

Cool hypergiants (Ia⁺ or Ia0) are a class of supergiant stars with T_{eff} below $\sim 10,000$ K. They are physically different from supergiants of luminosity class Ia. The usual Ia⁺ designation does not mean that they are always more luminous than the former, but they differ in their spectral properties. These stars show one or more broad emission components in the Balmer H α line profile, which is a signature of an extended atmosphere or of a relatively large rate of mass loss. Another important spectroscopic aspect of hypergiants is that their absorption lines are significantly broader than those of the Ia stars of similar spectral type and luminosity (de Jager 1998). ρ Cas and HR 8752 are the prototype objects of the yellow hypergiants (F–G Ia⁺). They are among the most massive (20–40 M_{\odot}) cool stars presently known. These stars exist near the Eddington luminosity limit, and exhibit a wide range of uncommon stellar properties. Their atmospheres are unstable, which causes quasi-periodic pulsation variability, strongly developed large-scale velocity fields, excessive mass-loss, and extended circumstellar envelopes.

We summarize three fundamental questions for the study of hypergiants:

- i.* Why do hypergiants of similar bolometric luminosity and spectral type as normal supergiants display the signatures of strong large-scale photospheric motions and enhanced mass loss? Why do these properties appear to be absent for normal supergiants?
- ii.* What is the evolutionary status of the yellow hypergiants, and how do they fit into the broader scheme of massive star evolution? Are they the likely progenitors of (Type II) supernovae in the not too distant future?
- iii.* Can an understanding of their atmospheric dynamics and circumstellar environments provide clues about the origin of the luminosity boundary for evolved stars? Do these dynamics characterize the hypergiants uniquely, or do they occur modified in other classes of luminous stars as well?

2. Microturbulence

A few years after *The Brightest Stars* de Jager (1984) published a theoretical paper which marked the beginning of a thorough study about the stability of hypergiant atmospheres, and which has consequently been pursued by many other workers in this field. It is put forward for the first time in this paper that atmospheric dynamics is a basic ingredient for understanding a temperature-dependent maximum luminosity limit extending across the entire upper Hertzsprung-Russell (HR) diagram. The classical Eddington limit is defined as the line in the HR-diagram where gravity equals the force produced by the radiation pressure due to electron scattering. Neglecting other atmospheric opacity sources, this results in a nearly horizontal line in the HR-diagram for stars with a single mass-luminosity relation. Hence, the classic limit cannot explain the absence of cool supergiants with $L_* \gtrsim 10^6 L_\odot$, because hot stars that are more luminous do exist. De Jager proposed instead that the local stability of these extended atmospheres is greatly altered by an outward acceleration due to the gradient of turbulent pressure which results from the local field of turbulent motions. The importance of the latter scales with luminosity. It causes the effective acceleration, which is due to the balance between gravity, radiation- and turbulent-pressure, to produce higher mass-loss rates for the intrinsically brighter stars. The influence of turbulence is particularly important for the cool supergiants for which the radiation pressure remains rather small. For this reason the theoretical luminosity limit of cool stars is occasionally termed the ‘de Jager limit’ (for turbulent pressure).

Studies of strong ‘microturbulence’ observed in the spectra of supergiants continue as an important subject of hypergiant research for obvious reasons. It increases the equivalent width of Fraunhofer lines by stochastic small-scale motions with wavelengths smaller than the optical scale height of the atmosphere. The line-of-sight velocity component of these movements samples only a limited part of the photosphere over which the spectral lines are formed. A pertinent problem in pinpointing the physical nature of stellar microturbulence is that it is often observed to exceed the sound speed in supergiant atmospheres. Microturbulence generally increases towards the hotter and more luminous stars.

It is frequently larger than the isothermal velocity of sound in the Ia and Iab supergiants.

In 1991 de Jager chaired an international congress in Amsterdam about instabilities in evolved super- and hypergiants. At the conference he presented the idea that stellar microturbulence is strongly related to the physics of atmospheric shock waves. Through numerical integrations of the hydrodynamics equations an observable microturbulent velocity is computed, assuming that the dependence of shock wave energy on the wavenumber is of the Kolmogoroff-type (a power law spectrum) (de Jager 1992a). Shock trains propagating outwards are a natural consequence of acoustic energy generation in cool stars with a subphotospheric convection zone. De Jager et al. (1997) subsequently showed that the thin heated layers trailing these shocks constitute the main part of the observed micro-‘turbulence’. A complex of successive hot sheets, distributed stochastically over the atmosphere, yields a stochastic distribution of thermal motions that, observationally, cannot be distinguished from a random field of small-scale hydrodynamic motions (de Jager 1998).

The application of this theory to the yellow hypergiant ρ Cas revealed that a field of atmospheric shock waves which is critically supersonic, or have a mean Mach number only slightly exceeding unity, reproduces the observed supersonic microturbulence velocity of 11 km s^{-1} . Remarkably, the hydrodynamic velocity field in the shocks remains very small, of the order of only 0.5 km s^{-1} . Nevertheless, the momentum provided by such weak shock wave trains, assuming spherical geometric symmetry, is sufficient to initiate the large mass-loss rates (typically a few times $10^{-5} M_{\odot} \text{ yr}^{-1}$) observed in cool hypergiants (de Jager 1996). These rates partly result from the very large stellar surface area (the mean photospheric radius of ρ Cas ranges between 400 and $500 R_{\odot}$), and the sonic point which is situated well inside the photosphere (de Jager et al. 2001). The field of stochastic shock waves provides on average outward directed momentum which diminishes the effective atmospheric acceleration and increases the atmospheric scale height.

3. Mass Loss

Evolutionary calculations show that yellow supergiants evolve along tracks of nearly constant luminosity, beneath an observational luminosity limit. This limit has been called the Humphreys-Davidson (HD) limit, when it was pointed out that the luminosity of the brightest blue stars is about a factor six higher than that of the luminous red stars. Very evolved luminous supergiants move *bluewards* in the HR-diagram because they shed copious amounts of mass to the circumstellar/interstellar environment in the red supergiant phase. During redward evolution the very high mass-loss rates (\dot{M}) reduce the stability of the convective layer, and below a critical envelope mass it contracts into a thinner radiative envelope, which causes rapid blueward evolution. For only a limited range of initial masses stars can become red supergiants, and evolve back far bluewards. The late stages in the fast evolution of these massive stars are relatively short. Typical values computed for stars with masses between 20 and $40 M_{\odot}$ are around one million years, with blueward tracks which last only a few

times 10^4 years. The high \dot{M} for very massive stars is however thought to have a decisive influence on these late evolutionary stages.

De Jager et al. (1988) presented a comprehensive table of empirical mass-loss rates for 271 objects all over the HR-diagram, together with a parameterization which holds for stars from early to late spectral types (Nieuwenhuijzen & de Jager 1990). \dot{M} primarily depends on the stellar luminosity L_\star . For hot stars there appears to be a rather linear dependence, whereas K and M stars deviate by about 3 dex from the average hot star dependence. This points to other parameters than L_\star (and T_{eff}) which influence the mass-loss rate (de Jager 1993). It seems imperative to ascribe the difference to the different physical mechanisms which drive the massive stellar winds in the hot and in the cool supergiants. These differences are apparent from the emission line components observed with high dispersion in ρ Cas at either or both sides of the Doppler displaced H α absorption core (Lobel et al. 1998). These complex line profiles indicate (quasi-) cyclic variations of the atmospheric circumstances and dynamics, which causes variable mass-loss rates that can occasionally increase to extreme values of a few $10^{-4} M_\odot \text{ yr}^{-1}$. The temporal variability observed in photospheric absorption lines is not correlated with the changes of H α ; the latter is at least twice longer than the former. Since H α forms higher, over a larger fraction of the atmosphere, it indicates that the atmosphere is dynamically velocity stratified, and the pulsation strongly enhances the density scale height compared to hydrostatic models.

Yellow hypergiants exhibit ‘eruptions’, which occur on time-scales much longer than the pulsation quasi-period (ca. half a century, say). In an outburst of 1945-46 ρ Cas suddenly dimmed and displayed TiO-bands in its spectrum, characteristic of the photospheric temperatures of M-type stars. Within a couple of years the star brightened up by nearly a magnitude (April '47), and a mid G-type spectrum was recovered around 1950. In 1985-86 the star showed a larger-than-average amplitude in the light curve, which can be associated with shell ejection events. Pulsation variability seems to be a common phenomenon in these stars. In his review on yellow hypergiants de Jager (1998) hypothesized that a distinction should be made between the periods in which these stars can be considered as fairly quietly pulsating, and when they are in the ‘explosive’ phase. During that phase the effective atmospheric acceleration practically vanishes, resulting in strongly enhanced mass ejection. Interestingly, it is suggested that the mechanism for outburst may be related to increased pulsation velocities during a period of instability that occurs when the star, during rapid blueward evolution, increases its pulsation amplitudes. The broader view emerges here that the exceptional atmospheric dynamics manifested by the yellow hypergiants is intricately related to their late evolutionary stage.

4. Circumstellar Environment

Little is known about the circumstellar environments of yellow hypergiants. The mid-IR silicate emission feature of ρ Cas is very weak, indicating the formation of dust only at very large distance from the surface. However, IRC+10420 is of later spectral type and possesses a very extended dust shell. It is commonly assumed that mass-loss from cool massive stars is primarily spherically symmetric.

The absence of observational evidence for strong magnetic fields in these supergiants and slow rotation does not readily support wind flows into a preferential direction. It is known that for most if not all stars wind flow is not spherically symmetric. Magnetic fields and rotation have a strong tendency to concentrate the gas that is leaving the star towards the equatorial plane, thus producing a disk rather than a spherical wind structure (de Jager 1993).

HST-WFPC images of IRC+10420 reveal a circumstellar environment with a bipolar symmetry, and jet-like features and arcs produced primarily in the equatorial region. A bipolar wind has also been proposed for ρ Cas (Lobel 1997), based on the phenomenon of line core splitting observed in optical absorption lines of very low excitation energy. ρ Cas' emission line spectrum is excited in the circumstellar environment with an excitation temperature of 3050 K. This emission spectrum can emerge from a fast bipolar wind which collides with denser circumstellar (or perhaps interstellar) material, expelled during its violent mass-loss history. Similar split line cores were also observed for HR 8752 in 1960-70, when it was the spectroscopic twin of ρ Cas. The line core splitting phenomenon is of a bewildering complexity, because the central reversals are permitted emission lines which appear in the core of metal absorption lines of resonance and subordinate transitions. ρ Cas' emission spectrum is not excited by a normal stellar chromosphere because its spectrum lacks the classic chromospheric indicators, except for H α . Long-term spectroscopic monitoring of the split profiles reveals that the central emission peak is static, while the intensity of either of the adjacent absorption components periodically intensifies and weakens. This supports the formation of the emission line spectrum at large distance from the star, where it does not share the photospheric pulsation movements below. The blue-shifted appearance of the central emission cores indicates their formation in an optically thick wind. On the other hand, we have also discovered forbidden [Ca II] emission lines in the spectrum, which reveals a very extended tenuous gas envelope surrounding ρ Cas. Prominent [N II] line emission is also observed in HR 8752.

Surprisingly however, the same metal core splitting phenomenon is observed in FU Ori objects. These young stellar objects have bipolar outflows, produced by disk accretion, with powerful outbursts of mass-loss. They are pre-main sequence objects with optical spectra resembling F- and G-supergiants. Interestingly, it has also been proposed that FUor eruptions are due to perturbations in a circumstellar disk caused by the passage of a compact companion on an eccentric orbit. There is presently no indication for a compact companion in ρ Cas, but clear evidence for an early B-type main sequence star in HR 8752 was obtained from continuous near-UV spectra observed with *IUE*.

Whether split absorption profiles are the signature of circumstellar disks which can obstruct strong wind outflow remains currently unanswered and requires further research. It appears however that they are spectral indicators of complex and dynamic circumstellar environments, which characterize the yellow hypergiants.

5. Atmospheric Velocity Fields

In 1990 de Jager published a short paper in *Solar Physics*. The paper is remarkable in that it provides an explanation for the problem of the ‘granulation boundary’ in the HR-diagram. This boundary has been inferred from the shape of spectral absorption line bisectors which incline oppositely when moving from the lower to the higher effective temperature regions in the HR-diagram. For the Ib supergiants the bisector turnover occurs around spectral types G0-5, but is poorly defined for the more luminous Ia and Ia⁺ stars. The spectra of F-type supergiants display uncommonly broad absorption lines which are ascribed to a well developed large-scale velocity field. The large macrobroadening cannot be attributed to rapid rotation (i.e. large $v\sin i$ -values) for these evolved and very extended stars. For example, the modeling of line profiles in ρ Cas yields highly supersonic macroturbulent velocities of $\sim 25 \text{ km s}^{-1}$. De Jager (1990) proposed that for stars to the left of the boundary, in the optically thin regions of the atmosphere above the convection zone, internal gravity waves develop which involve a large part of the line forming region. To the right of the granulation boundary the atmospheres are in convective equilibrium, and gravity waves would only affect the smallest optical depths, which hardly influences the line profiles.

In a major paper which was published the year after, de Jager et al. (1991) provided the mathematical and physical foundation for these insights. The most important wavelengths in the spectrum of gravity waves are close to the atmospheric cut-off wavelength. The latter results from radiative damping and the atmospheric curvature. It is pointed out that in the highest atmospheric levels only the very low-mode (long wavelength) gravity waves are possible. For supergiant pulsation, high l modes are not expected because the wavelength of internal gravity waves propagating in these extended atmospheres should exceed this cut-off wavelength. In deeper layers the damping cut-off wavelength becomes gradually shorter and higher gravity waves become possible. The more extended the atmosphere the lower the mode-number of gravity waves that may develop. However, gravity waves cannot propagate inside convectively stable regions where their minimum period (the Brunt-Väisälä period) becomes real and non-zero. Gravity waves propagate mainly in the horizontal direction, along the stellar circumference. They do not propagate strictly vertically.

The application of this theory (de Jager 1998) to the yellow hypergiants ρ Cas and HR 8752, and to the white hypergiant HD 337579, provided a number of impressive theoretical results. Based on the *diagnostic diagram*, which plots the periods of pressure- and gravity-waves against their respective spectra of possible wavelengths and the observed quasi-period(s), he showed that these atmospheres are dominated by systems of gravity waves with in some cases shock waves superimposed. For ρ Cas the long-period waves are due to gravity waves of the shortest allowed wavelengths and periods, with fairly high l -values. The short-period components show the presence of pressure waves with wavelengths of about half the stellar radius. l -values exceeding unity are consistent with the finding for ρ Cas (Lobel et al. 1994), from an improved Baade-Wesselink pulsation test, that photospheric *radial* pulsations must be discarded to combine T_{eff} -changes with the co-eval radial velocity- and light-curve, observed over a complete variability period. The quasi-periodicity observed in the light-curves

of cool hypergiants therefore results from a complex, but law-abiding, interplay of atmospheric (non-radial) pulsation modes due to gravity and acoustic waves.

6. The Yellow Evolutionary Void

In 1995 Nieuwenhuijzen & de Jager published a classic paper on the atmospheric accelerations and stability of supergiant atmospheres. Their research provides a well-founded theoretical explanation for the conspicuously sparse amount of white (late A to early F-type) supergiants in the HR-diagram. At the Amsterdam conference de Jager (1992b) raised the question of why most of the known yellow hypergiants appear to cluster around $6500 \text{ K} \leq T_{\text{eff}} \leq 7500 \text{ K}$ with different luminosities, while the area around $10,000 \text{ K}$ and $\log(L_{\star}/L_{\odot}) \geq 5.7$ is nearly devoid of stars. Due to the natural deficiency of cool supergiants it is possibly hard to judge the reality of their absence around the upturn of the HD limit, but current population studies support only a minimal number of very luminous white supergiants. This area was tentatively baptized the ‘evolutionary void’ after detailed calculations revealed that hydrostatically stable solutions cannot be computed for the atmospheres of *blueward* evolving yellow hypergiants at a lower temperature boundary of $T_{\text{eff}} \simeq 8300 \text{ K}$. These calculations involve a time-independent solution of the momentum equation, which considers the Newtonian gravity acceleration derived from the evolutionary mass, the gas, radiation and turbulent pressure gradients, and the momentum of the stellar wind. The latter requires the observed mass-loss rate. An ‘effective acceleration’ for the atmosphere is obtained iteratively, but which becomes negative at the cool border of the void. The outwards directed net force causes an unstable atmosphere above 8300 K . A remarkable byproduct of this study is that as stars move along their track, for time scales longer than the dynamic time scale of the atmosphere, the atmosphere continuously adapts to the new $(L_{\star}, T_{\text{eff}})$ -values, and remains stable without reaching the Eddington limit. Current practice of determining the stability limit by extrapolating hydrostatic models to a ‘modified’ Eddington limit (i.e. utilizing a flux-mean opacity for the atmosphere which includes line opacity) is therefore not justified. When a real star slowly changes its effective gravity acceleration to zero during evolution the atmosphere puffs up, thereby decreasing the opacity to the classic electron scattering value.

Over the past few years Drs. de Jager and Nieuwenhuijzen commenced a profound investigation of several individual cool hypergiants to which their theoretical developments are being applied (Nieuwenhuijzen & de Jager 2000). Atmospheric model parameters of HD 33579 have been determined via the ‘spectral diagnostics method’ and reveal that it is a redward evolving (high-mass) supergiant inside the void. For such a star the void is not forbidden. HR 8752 and IRC+10420 have lower masses and evolve bluewards, currently approaching the void. Several independent studies have demonstrated a significant overabundance of sodium in ρ Cas. It is brought to the photosphere by dredging-up, which would support its post-red supergiant phase. De Jager & Nieuwenhuijzen (1997) suggested that the recurrent eruptions in yellow hypergiants occur when these stars approach the cool boundary of the void, and ‘bounce off’ redward (for a graph see Fig. 1 of Nieuwenhuijzen & de Jager 2000). This bouncing against the void may explain why most of the cool luminous hypergiants cluster

near its low-temperature boundary, while the identification of hypergiants of later spectral type, possibly like VY CMa (of M-type), is seldom. An increase of the photospheric temperature of HR 8752 by 3000 K–4000 K has been observed based on high-resolution spectra collected over the past thirty years. The effective temperature of IRC+10420 has been as low as 5270 K and increased to ~ 7000 K in 1992. The natural question arises whether (apparent) evolutionary changes on human time-scales result from an actual active reconstruction of the stellar interior, or by some hitherto unknown envelope mechanism? Is there a global instability mechanism in these stars other than stellar pulsation, which changes their spectral types, perhaps triggered by some internal or external cause? Is the void an eternal obstacle for their evolution and will the yellow hypergiants eventually fade as supernovae, or will they rapidly evolve across the hypergiant void into early A-type supergiants (e.g. the least luminous S Dor stars), after having lost large amounts of mass? Time will tell.

7. Future Work

As is the case with all research at the forefront of science, the present-day developments are the most exciting. To avoid disclosing research results prior to the main publication (de Jager et al. 2001), we summarize some important general aspects of hypergiant atmospheric stability, and the lines along which further investigations are planned. New studies show that different areas in the upper HR-diagram can be delineated where the effective acceleration in the upper part of the photosphere is negative, or directed outwards. Stars like ρ Cas, HR 8752, and IRC+10420 are situated close to this line. Another aspect of their dynamic stability is that the sonic point (the point where the wind velocity equals the sound speed) of the stellar wind is situated inside the photosphere. Matter which is driven beyond this point escapes freely into space, causing high mass-loss rates.

Parallel to these developments is the study of the behavior of the adiabatic indices in the atmospheres of luminous supergiants. An early study (Lobel et al. 1992) showed that Γ_1 assumes values below $4/3$ in low-gravity hydrostatic model atmospheres. This corresponds to zones of increased atmospheric destabilization due to partial hydrogen and helium ionization. The study is presently further improved by evaluating Ledoux' stability integral $\langle \Gamma_1 \rangle$ for realistic envelope models (Lobel 2001), including the effects of photo-ionization and the dilution of radiation pressure in the extended atmospheres of these stars. Important dependencies on the atmospheric acceleration and effective temperature have been demonstrated so far.

Future work will focus on the interrelations between these different stability criteria, and their various specific implications. It appears to us that considerable progress will be accomplished by integrating the fully time-dependent hydrodynamic equations, and incorporating the various acceleration mechanisms in the equation of motion, together with the increased atmospheric compressibility due to partial LTE- and NLTE-ionization. These simulations could for example model the velocity stratification observed for ρ Cas' atmosphere. The further refinement of regions of dynamic instability in the upper portion of the



Figure 1. Kees de Jager inspecting the Observatori del Teide at Izana on the island of Tenerife (Canary Islands, Oct. 1999). The Gregory Coudé solar Telescope towers in the background.

HR-diagram, and a continuous spectral monitoring program of HR 8752 (de Jager et al. 2001), for which an outburst seems imminent, is in progress.

To conclude this overview, it is safe to say that our understanding of hypergiants has considerably changed and improved over the past two decades. At the same time, lots of new and pertinent questions have been raised about these exceptional objects. We owe much of this progress to the dedicated and continuing work of one person; Cornelis de Jager, who is a guide and has been the mentor of many researchers in astronomy and astrophysics.

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