ATMOSPHERIC DYNAMICS OF LUMINOUS STARS

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ABSTRACT. A review is given of data and theories on the motion fields in super and hypergiants with special reference to LBV's. We show that the radiative momentum flux is incapable of driving the episodical bursts of mass loss of these stars, and that there are several indications that the LBV-phenomenon is hydrodynamically driven. The sum of turbulent and radiative accelerations in the atmospheres of the most luminous stars compensates the gravitational acceleration for stars near the Humphreys-Davidson limit. This explains their atmospheric near-instability. The motion field in the atmosphere of a typical LBV consists mainly of low-order gravity waves, while acoustic waves are rapidly damped. These gravitation waves may be stochastic rather than coherently ordered. These stochastic pulsations are assumed to be responsible for the LBV phenomenon.

1. PHYSICAL CONDITIONS IN THE ATMOSPHERES OF VERY LUMINOUS BLUE STARS

1.1. Momentum of stellar winds at the upper brightness limit of stellar existence

A review of mass loss rates in the upper part of the Hertzsprung-Russell diagram was published recently by De Jager, Nieuwenhuijzen and Van der Hucht (1988). These data allow us to compare the momentum flux of the stellar winds Mv_∞ (where M is the rate of mass loss and v_∞ the asymptotic stellar wind velocity) with that of the stellar radiation flux L/c. We made these calculations for stellar parameters valid at the Humphreys-Davidson limit, for which we know L and T_{eff}. The values of M were read from our mass loss review while for v_∞ a relation was used derived earlier by De Jager (1984). The results, shown in Table 1, demonstrate that along the whole upper limit of stellar existence the mass flux momentum losses are smaller than those of the radiation flux momentum; hence the stellar radiation flux could, at least in principle, account for the quiescent average stellar mass loss momentum flux. But it is clear from the data in Table 1 that this will no longer be the case when the rate of mass loss would increase by a factor > 3 to 5, as happens in LBV mass ejections. Another, presumable hydrodynamic, explanation has then to be sought. This is our first indication that the

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LBV phenomenon may be hydrodynamically driven.

Table 1. Comparison of radiative versus wind momentum fluxes along the Humphreys-Davidson limit;

$\log T_{eff}$	$\log \frac{L}{L_\odot}$	$\log \dot{M}$ $(M_\odot yr^{-1})$	v_∞ $(km\ s^{-1})$	$\dot{M}v_\infty \times 10^{-28}$	$\frac{L}{c} \times 10^{-28}$	$\frac{\dot{M}\ v_\infty c}{L}$
4.4	6.3	- 4.5	520	10.3	25.5	0.39
4.1	6.1	- 4.5	160	3.09	16.1	0.19
3.8	5.9	- 4.0	47	2.96	10.1	0.29
3.5	5.9	- 3.5	14	2.79	10.1	0.27

1.2. Acceleratîons and stellar wind velocities in the upper blue part of the Hertzsprung-Russell diagram

For stellar parameters valid in the upper part of the Hertzsprung-Russell diagram Nieuwenhuijzen and De Jager (1989) investigated the physical properties and the various accelerations, such as radiative, dynamic wind and turbulent accelerations. We refer to their Figure which gives the ratios g_{out}/g_{grav}, g_{turb}/g_{rad} and v_{wind}/s (where s is the velocity of sound). Here, g_{out} is the sum of all outward accelerations: those due to radiation pressure, turbulence and the stellar wind.
In those figures the relevant quantities are given for an optical depth $\tau_R = 0.1$, which is about the level where most of the Fraunhofer lines of average strength are formed in the atmospheres of hot stars.
Noteworthy, and perhaps important for our understanding of the LBV phenomenon is that the area occupied by the LBV's coincides fairly well with the area where the rate g_{turb}/g_{rad} assumes its largest values, with a maximum of about 0.5. This is our <u>second indication</u> that the LBV phenomenon may be driven by hydrodynamic phenomena.

In addition it appears that the upper boundary of the LBV region coincides fairly well with the line where $v_{wind}/s = 1$ at $\tau_R = 0.1$. This means that only a slight disturbance of (a part of) the atmosphere, such as a local (pulsating) outward motion, would be sufficient to shift the sonic point of the stellar wind into much deeper layers, where the density is larger, which would then cause a large increase of the rate of stellar mass loss in that area of the stellar disc. This may explain the observed semi-regular mass ejections, and this may be our <u>third indication</u> that the LBV phenomenon is a hydrodynamic one.

We give an example applied to a real star. For the L and T_{eff} values at the position in the HR diagram of a typical LBV, P Cyg, we take (De Jager et al.), 1988; star # 145): Log $T_{eff} = 4.3$; $\log(L/L_\odot) = 5.93$, the quiescent rate of mass loss is $\log\dot{M}$ $[M_\odot/yr] = 2.10^{-5}$. Its "estimated mean mass" is 32 $M_\odot$. In the photosphere, at $\tau_R = 0.1$: $s = 21$ km s^{-1}. If that outward velocity would occur at the depth level $\tau_R = 2/3$ (just to give an example) the star's mass loss would increase to 2×10^{-4}; an enhancement by a factor 10! If, as seems likely, we are not dealing with strict radial pulsations but rather with localized (non-radial or stochastic) pulsations the increase in the rate of mass loss would be smaller, proportional to the area involved. But for pulsations for which the above mentioned outward velocity would occur at larger depths the rate of mass loss would become larger, proportionally to the increased density at the level considered.

1.3. The influence of turbulent pressure on atmospheric instability

Any directed gas motion excerts a dynamic pressure, which is the transport of momentum $\rho v.v.$ associated with the gas motion. In a turbulent medium the gas motions are distributed stochastically. Each moving "element" has its own dynamic pressure, and the integrated dynamic pressure of a turbulent gas, the so-called turbulent pressure is the momentum flux density tensor $\rho.v_i.v_j$. For a field of accoustic waves the turbulent pressure is

$$P_t = 0.5\ \rho<\xi_t^2>,$$

where $<\xi_t^2>^{\frac{1}{2}}$ is the mean squared turbulent velocity component. For a field of shock waves the factor is 1/3 (Ulmschneider et al., priv. comm.).

The value of the turbulent acceleration g_t in a stellar atmosphere can be determined on the basis of a determination of the microturbulent velocity component, if that quantity is known as a function of the height in the stellar atmosphere. This has so far been done observationally for six stars; Figure 1 gives $g_{out}/g_{grav} = (g_t + g_{rad})/g_{grav}$ as a function of Δ log L, where the latter quantity is the vertical separation in the Hertzsprung-Russell diagram of the star's luminosity from the luminosity at the Humphreys-Davidson limit (Humphreys and Davidson, 1984).

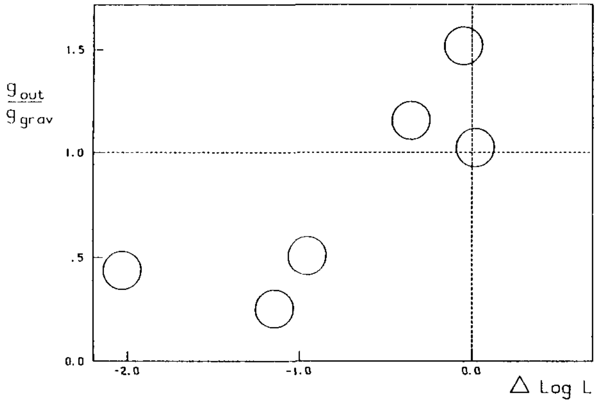

Figure 1: Ratio g_{out}/g_{grav} for six well-studied super and hypergiants. The data are plotted against the vertical distance of the star to the Humphreys-Davidson limit. The absolute value of the ratio approaches unity at the limit.

It appears from the Figure that for $\Delta \log L \rightarrow 0$, $g_{out} \rightarrow g_{grav}$. This explains the stellar atmospheric instability at and above the Humphreys-Davidson limit.

Thereby a distinction should be made between hot and cold stars. For $T_{eff} \lesssim 10^4$, $g_{out} = g_{turb}$ (the influence of radiation is negligible), but for hotter atmospheres g_{rad} becomes important. So far we have investigated one hot star, HD 80077 (B2 Ia+; Carpay et al., 1989). For this object we found (Table 2) that $g_{turb} < g_{rad}$ but g_{turb} is certainly not negligible, being one-fourth to one half the radiative acceleration. It would be highly important to study more hot stars of various temperatures, along the HD limit.

Table 2. Acceleration in HD 80077 (B2 Ia+) at two optical depths. The g-values are in cm s^{-2}.

τ_{Ross}	g_{grav}	g_{rad}	g_{turb}	g_{eff}
0.24	- 100	+ 80	+ 15	+ 5
0.08	- 100	+ 73	+ 20	+ 7

1.4. The large-scale ("macroturbulent") motion field

This motion component is difficult to determine since it needs high-dispersion spectra, while also knowledge of all other broadening mechanisms is required. For Alpha Cyg (A2 Ia) we found a bimodal distribution of the large-scale vertical motion component, with values of + and - 14 km s^{-1}, (Boer et al., 1988). This velocity is supersonic. This observational result implies the occurrence of large up- and downward elements on the stellar surface. Since the average (r.m.s.) stellar velocity fluctuation is 2.3 km s^{-1}, there must be on the average 30 to 40 elements on the visible surface with, hence, average diameters of 30 x 10^6 km. Also in the less extreme supergiant Alpha Sco (M1.5 Iab) there are indications for a bimodal distribution of the large-scale motions, but the amplitudes are smaller (rather of the order of 5 km s^{-1}) and it is therefore more difficult to determine them (De Koter, 1989).

2. THE PHYSICS OF THE MOTION FIELD

2.1. The dispersion function

Assuming plane waves and adiabatic disturbances the dispersion function gives the relationship $\omega(k)$ between the wave number k and the wave frequency ω. Neglecting magnetic effects two kinds of waves remain for consideration:
the G waves (gravity waves; gravity being the restoring force);
the P waves (pressure or acoustic waves; pressure difference restores).

Instead of giving the $\omega(k)$ relation it adds to clarity by giving the T(L) relation instead, where $L = 2\pi/k$ is the wavelength and $T = 2\pi/\omega$ is the wave period. Figure 2 gives such a diagram, constructed for the L, T_{eff} and M values expected to apply to a star with characteristics similar to those of a typical LBV, P Cyg.

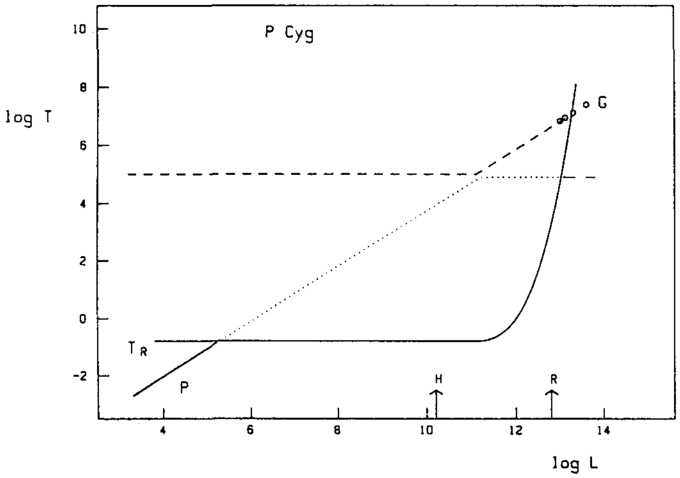

Figure 2: Diagnostic diagram for the motion field in a typical S Dor star (LBV); we chose the parameters of P Cyg.

The diagram is valid for an optical depth $\tau_R = 0.1$, where we derived (Nieuwenhuijzen and De Jager, 1989):

log T = 4.188; log P = 0.760; log ρ = -11.467. The stellar mass is taken as 32 $M_\odot$, and the accelerations are

g_{grav} = - 143; g_{rad} = 112, g_{wind} = 4; g_t = 14. Hence g_{eff} = -15.

For other stars similar graphs can easily be derived.

Important lengths are indicated in the diagram: H is the atmospheric density scale height; R the stellar radius.

2.2. Motions cannot exist at all wavelengths; restriction of the domains

Although, in principle, waves can occur all along the lines marked G and P in Figure 2, the actual domain of their occurrence is restricted because for certain wavelength regions the waves do not develop or are extinguished in a time shorter than one wave period. There are several such damping mechanisms (for more details we refer to De Jager et al., 1989).

a. Radiative damping of waves occurs because of radiative exchange of energy between the "hot" and "cold" parts of the wave. The line labeled T_R gives the e-folding time of radiative damping as a function of wavelength L. Only in those parts of the diagram where the P or G lines are situated below the line T_R, waves can exist virtually undamped during a period longer than one wave period. Above it they are damped in less than a wave period and thus cannot develop. The effect is only valid for non-compressible waves such as gravity waves; for acoustic waves the T_R curve is a lower limit.

b. Atmospheric curvature effects tend to reduce the restrictions due to radiative damping because that effect is working less efficiently when the wavelengths of the surface waves are so long that the curvature of the atmosphere prohibits radiative exchange. For a star like P Cyg this effects starts to work for $L = 0.1\ R_{star}$. The effect is smaller and the consequent radiative damping time longer for longer wavelengths, but the precise course of the line has not yet been calculated. Awaiting further research, the line drawn in Figure 2 serves merely as an illustration.

On the basis of these considerations we conclude that in the atmosphere of a star like P Cyg the P waves only occur for short wavelengths. The G-waves are only possible for fairly long wavelengths, longer than the stellar radius. At the long wavelengths of the gravity waves standing waves can only develop for discrete wavelengths given by $L(m) = 2\pi R/m$, where m is an integer. But since radiative damping still plays a role for these waves they may exist only for a few small m values.

2.3. Coherent non-radial or stochastic pulsations?

Another possible consequence of the situation as outlined in Figure 2 is the fact that it appears difficult for a system of standing non-linear oscillations to develop. Any single wave, once excited, will fairly rapidly damp out. This is the reason why we have suggested in various places (De Jager, 1980; Boer et al., 1988) that the large-scale motion field in super- and/or hypergiants may be a stochastic motion field rather than an ordered system of nonlinear pulsations. To show the evidence we give in Figure 3 the variation of the radial velocities of Alpha Cyg (A2 Ia) as given by Lucy (1976) and as modelled by Schellekens et al. (1989) by a field of stochastic motions.
This is no proof, evidently, that the motions on Alpha Cyg are like that, but it shows the possibility.

We think that detailed analyses of the atmospheric motion fields of S Dor stars may be very rewarding.

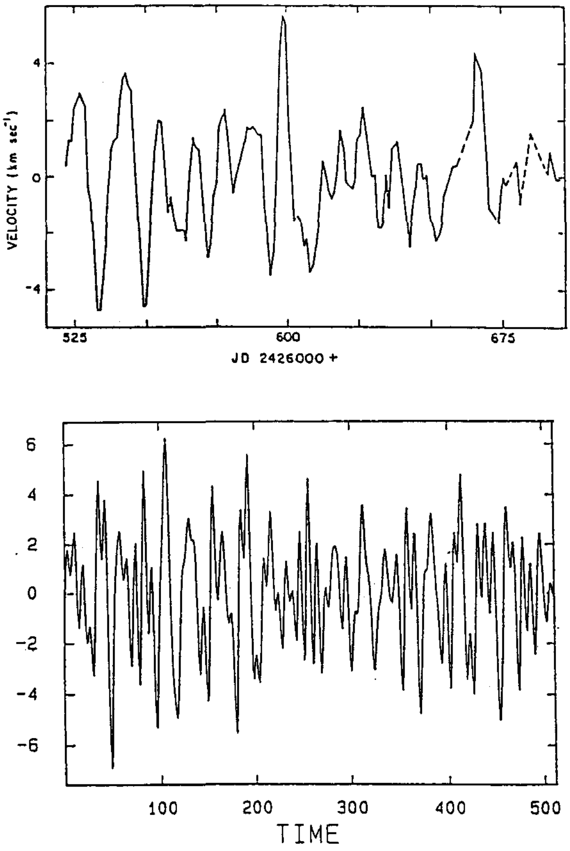

Figure 3: Comparison of observed (above) and modelled radial velocity variations for α Cyg; note the different scales of the abscissae.

3. CONCLUSION ON THE MOTION FIELD IN SUPER AND HYPERGIANTS

We have shown in this review that there are various indications that the LBV phenomenon may have hydrodynamical causes. Radiation pressure and its fluctuations do not seem capable of driving the stellar bursts of episodic mass loss, while pulsations of a part of the stellar surface may well provide a working mechanism. The motion field in a typical LBV (we choose the parameters of P Cyg) may consist mainly of low-mode gravitation waves, and there is evidence that the motions are stochastic and not coherently ordered. By such stochastic pulsations, not necessary all of the same amplitude, episodical bursts of enhanced mass loss may occur.

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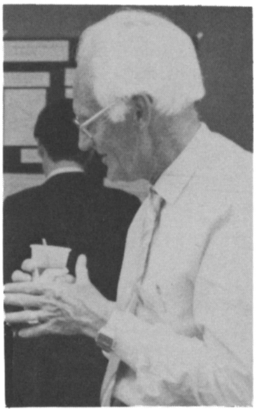

C. de Jager

DISCUSSION

Sreenivasan: We have shown, as I mentioned briefly in my talk, that α Cyg has a number of g-modes that are overstable (up to $l = 10$ and $l = |m|$ prograde modes). There are presumably more modes that are overstable. The frequencies are close and mode-coupling is likely. This has the consequence that observations may look like "stochastic" pulsations as you said. That was also the conclusion of Lucy who analyzed Paddock's observations. The strong differential rotation would induce shear turbulence in such stars which could be the source of your turbulent pressure gradient in the atmospheres of these objects.

De Jager: I agree with what you say but wish to stress that it is virtually impossible to decide between stochastic and well-ordered non-linear pulsations on the basis of Paddock's series of observations; three years is still too short!

Maeder: From the relatively long periods of the short-term pulsations of LBV's, you assigned them to blueward tracks. By themselves, these relatively long periods only imply a lower average density, consistent with the fact that LBV's experience high mass-loss rates. They can be on either redward or blueward tracks, or just making horizontal excursions back and forth in the H-R diagram.

De Jager: I see your point and realize that evolved blue supergiants will not return on their tracks early enough if they have not lost enough mass. That is the problem for evolutionists to solve. My point is that there is some evidence that they are far evolved, and hence may start losing mass rapidly only on their blueward track. I realize that this is contrary to what evolutionists want.

Appenzeller: A few blue supergiant stars, such as #12 in the Cygnus OB2 association, are about as luminous as LBV's but show no variability or exceptionally strong winds. Their effective temperatures may be just cool enough to be safe from radiation pressure effects. How important are turbulent-pressure effects in such stars?

De Jager: The star that you mention lies well above the range occupied by LBV's in the H-R diagram. Its absolute magnitude makes it a hypergiant. The apparent faintness of that star makes it difficult to obtain the high-resolution spectra needed for a good analysis of its atmospheric motion field. But I would guess that there is strong atmospheric turbulence.

Humphreys: Cyg OB2 (or VI Cyg) #12 is a B8 hypergiant, an extremely luminous star. HD 33579 in the LMC is a similar star, with apparent visual magnitude about 9.5, and would be a good candidate for your analysis.

De Jager: According to its position in the H-R diagram, Cyg OB2 #12 should have an atmosphere in which g_{grav} is reduced by ~ 70% by radiation and turbulence may account for the remaining 30%; it is a pity that high-resolution spectroscopy of this star is so difficult. Thank you for your suggestion about HD 33579; we will apply for observing time!

Owocki: (1) I would like to point out that pulsation-driven mass loss in late-type stars has been investigated quite extensively by Lee Ann Willson and her colleagues. A nice review of this field by John Castor appeared in the volume honoring Prof. de Jager's retirement (*Instabilities in Luminous Early-Type Stars*, ed. by Lamers and de Loore, 1987). (2) Recent work that I have done, in which the effects of pulsations at the base, but including radiative force, are simulated numerically, seems to suggest that the mass-loss rate should be variable. The timescale, however, is about a day, much faster than the large variations of LBV's.

Hillier, Niemela

Davidson, Nieuwenhuijzen, Klapp, Gosset