RADIAL AND NON-RADIAL PULSATIONS IN WOLF-RAYET STARS AND IN SUPERGIANTS.

André Maeder
Geneva Observatory
CH-1290 Sauverny, Switzerland

1. INTRODUCTION

The two subjects of the variability of WR stars and of supergiants are still in their infancy and are certainly promised to a great development in coming years. The physics and pulsation properties of WR stars and supergiants, although both kinds of stars result from massive star evolution, are indeed very different and will be discussed separately.

2. OBSERVATIONS ON WR STAR VARIABILITY

The classical view about the variability of WR stars is that by Moffat and Haupt (1974; cf. also Lamontagne and Moffat, 1986). In extensive photometric observations in the continuum and emission lines of seven WR stars (five WN, two WC) they observed no significant variations with time scales of 2 minutes to 1 hour, as was expected from studies of the pulsational instabilities of massive helium stars. These authors found, however, that some WR stars show variations, particularly in the emission lines, over a few days and even over hours, and they suggested the fluctuations to be caused by orbital effects in close binary systems containing a WR and a neutron star (cf. Moffat, 1982). Like the previous authors, Weller and Jeffers (1979) observed no variation in line strength for O and WN stars; however they found several spectral features of WC stars to vary on time scales less than one hour, which is a particularly interesting finding.

Vreux (1985) has recently claimed that the binary origin of the variations in the so-called "WR + compact companion" systems is doubtful. He showed that the periods of variations in the emission lines of different WR stars are in some cases surprisingly identical and in other cases just related by a simple multiple factor. He therefore suggested that the emission line variability, rather than being due to spiralling-in neutron stars, is an intrinsic stellar property and is due to non radial pulsations in single stars (cf. Vreux et al., 1985).

For now we conclude that if there is no doubt about the reality of

J.-P. Swings (ed.), Highlights of Astronomy, 273–281.

https://doi.org/10.1017/S1539299600006547 Published online by Cambridge University Press

pulsations in some WR stars, particularly in WC stars, the nature of the pulsations (binary motions, non radial, radial etc.) is uncertain. The identification of the pulsations is made very difficult by the fact that pulsations cannot be observed directly: WR stars generally have extended optically thick winds which do not allow the star itself to be seen. Moreover, we are still very ignorant about the response of an extended non-static envelope to inner pulsations: the interior and the extended envelope have different characteristic times and the matching of these two different physical systems has to be investigated in detail.

3. THEORETICAL STATUS OF WR PULSATIONS

WR stars are nowadays considered by most authors, with substantial justifications, to be bare cores in the He-burning stage. Most of these objects are likely to result from initial stellar masses larger than 40 $M_\odot$. Since long, the instabilities of helium stars have been investigated, in particular by the Liège group (cf. Boury and Ledoux, 1965) and also by Simon and Stothers (1969, 1970). Above a critical mass of 16 $M_\odot$ (cf. Noels and Maserel, 1982; Noels and Magain, 1984), the He-stars are vibrationally unstable. The driving mechanism of the instability is the nuclear energizing of pulsation in the stellar core, the so-called Eddington's ε-mechanism. However, we must remark that a WR star is likely to have some significant differences with a chemically homogeneous He-star: as a result of evolution, μ-gradients are present inside WR models; in WNL stars even an hydrogen gradient is likely to exist in the outer layers.

Do we expect radial or non radial oscillations in WR models? Let us firstly discuss the non radial case. The driving of non radial oscillations by central nuclear energizing is in a very unfavourable situation, because the amplitudes $\delta T/T$, $\delta\rho/\rho$ tend to be zero at the stellar center and no efficient pumping of energy can occur there (cf. Simon, 1957). This explains why Kirbiyik et al. (1984), in an investigation of non radial oscillations for WR models, found these stars to be stable for the low harmonics ℓ; they noticed however the appearance of instabilities for high degrees of harmonics (ℓ = 15). Noels and Scuflaire (1986) interestingly showed that, while there is no driving of non radial oscillations in WR stars to be expected from He-cores, the H-burning shells may produce some efficient driving of non radial pulsations. The periods found are of the order of a few hours. There is, however, a limitation: the H-shell is, if any, only present for a very short time in WR stars. In the case studied by Noels and Scuflaire it lasts only 6000 years. Indeed, most WR models (cf. Maeder, 1981) even do not exhibit an H-burning shell. This is particularly obvious if we remember that WNE as well as WC stars no longer have hydrogen at their surface; thus only a fraction of the WNL stars could have an efficient driving from the H-shell.

The case of radial oscillations in WR stars is much more promising since the driving of pulsations can be produced by core nuclear burning. Noels and Gabriel (1981) have found WR models to be unstable during a limited fraction of the WR stage, centered on the time of maximum core extension; however, when the star becomes a WC star, the stability of their models is restored. Maeder (1985) has found that WR star models, evolved with mass loss at the observed rates, enter the unstable regime when H/He = 0.3 at the stellar surface and that the star remains unstable during all the following WR stages; the pulsation periods are in the range of 15 to 60 minutes. The differences between the two above sets of models may probably be assigned to the mass loss rates $\dot{M}$ considered. The high mass loss rates are evidently an essential condition for maintaining instability during the WR stage. Lower mass loss rates favour chemical inhomogeneity during evolution, make higher $\rho_c/\bar{\rho}$ ratios and produce a shorter unstable phase around the time of the minimum value of $\rho_c/\bar{\rho}$. From my models I estimate that the minimum $\dot{M}$-value to keep the WR star unstable during all the WR stage lies well in the observed range as given, for example, by Conti (1982).

Any mixing process, such as overshooting, turbulent diffusion etc., by favouring the chemical homogeneity and thus reducing the ratio $\rho_c/\bar{\rho}$, would enhance the vibrational instability of WR stars (cf. Maeder, 1985). The same consequence can be inferred concerning the excess of mass loss due to mass transfer in binary systems.

The unstable WR models occupy a well defined mass-luminosity relation $\log L/L_\odot = 3.8 + 1.5 \log M/M_\odot$ (cf. Maeder, 1985), which is characterized by a large overluminosity with respect to the main sequence. The above finding that WR stars are closely associated to an evolutionary stage where vibrational instabilities are present to some extent meets the repeated claims by Thomas and coworkers (e.g. Costero et al., 1981 and subsequent discussions) that some deep-seated non-static processes cause the WR phenomenon. At present we cannot assume that vibrational instability is the only process responsible for the WR phenomenon, but it is a very good candidate. Radiation is also likely to be responsible for the high mass loss of WR stars (cf. Pauldrach et al., 1985b), in particular since WR stars may have much higher T_{eff} than previously considered (cf. Pauldrach et al., 1985a). For now we do not know whether radiation or pulsation is the main effect responsible for the WR phenomenon. However I want to emphasize that the very high L/M ratio of WR stars is likely to be at the origin of both pulsation and radiative effects. Thus, the very large L/M ratio is probably the deep physical reason for the WR phenomenon.

4. SUPERGIANT VARIABILITY: NEW EVIDENCES FOR NON RADIAL PULSATIONS

Recent reviews about supergiant pulsations were made by de Jager (1980), Maeder (1980), Percy and Welch (1980) and A.N. Cox (1985) who provides many new interesting theoretical results on the instabilities of supergiants and early-type stars. The main features of supergiant variability (cf. Abt, 1957; Maeder and Rufener, 1972; Sterken, 1977, 1981; Burki,

https://doi.org/10.1017/S1539299600006547 Published online by Cambridge University Press

1978; Maeder, 1980; van Genderen, 1980, 1985, 1986) are the following ones:

- All spectral features of supergiants may be variable: brightness, colour, radial velocity, spectral type, line profile, emission features.
- The variations are cyclic, rather than strictly periodic; however, the cycles are generally stable (cf. Sterken, 1981).
- The amplitudes of variations are irregular; the most luminous supergiants show hourly variations superimposed on slower variations.
- The amplitudes generally increase with the luminosity of the supergiants considered. However, there is a small local maximum for the early B-supergiants, and very large amplitudes (~0.8 m) are reached for the red supergiants.
- Some supergiants have pathological behaviour, they show phases of quiescence, erratic variations, mode switching, such as for example 89 Her (F2Ia) and HD 161796 (F3Ib) studied by Burki et al. (1980) and Fernie (1981, 1983).
- There is a period-luminosity-colour relation with periods of a few days for B supergiants to periods of hundreds of days for red supergiants (cf. Maeder, Rufener, 1972).
- The mean observed period is larger than the period P_o of radial pulsation in the fundamental mode. This is particularly the case for the early B-type supergiants, where the difference can reach a factor of 10 (cf. Maeder, 1980; Percy and Welch, 1983; Ferro, 1985; van Genderen, 1985), and it has generally been concluded that this is due to non radial pulsations. However, Lovy et al. (1984) call the attention about the evolutionary effects on the pulsation periods and on the period differences between bluewards and redwards evolutionary tracks.
- Other evidences in favour of non radial oscillations have also been given. In the study of α Cyg data, Lucy (1976) has identified 16 periods between 6.9 and 100.9 days, some of which appear in pairs. The small colour variations for supergiants with respect to what would be the case for a pure T_{eff} variation may also be considered as an indirect evidence for non radial oscillations (cf. Percy and Welch, 1983; van Genderen, 1986).

A break-through has been made by high resolution spectroscopy which has shown periodic travelling bumps in the lines of many early B-type stars (cf. review by Smith, 1981). More recently travelling bumps have also been found in the line profiles of some O-type stars and OB supergiants (cf. Smith and Ebbets, 1981; Ebbets, 1982; Vogt and Penrod, 1983; Baade, 1984a,b; Baade and Ferlet, 1984; cf. also Baade, this Joint Discussion). A nice example of travelling bumps in OB stars is the case of ζ Ophiuci (O9.5 Ve, v_{sini} = 370 km/s) which shows (cf. Vogt and Penrod, 1983) at the 1% level well defined line distorsions propagating uniformly across the absorption line profile of λ 6678 HeI with characteristic time of 5 h. The authors gave good arguments in

https://doi.org/10.1017/S1539299600006547 Published online by Cambridge University Press

favour of non radial oscillation in sectorial prograde mode with $\ell = 8$ and $m = -8$.

One has to be careful that travelling bumps are features which are different from the UV absorption components, which were interpreted as evidences of relatively high velocity shell ejections or puffs (cf. Lamers et al., 1978; Heck et al., 1980) and which stay the same for weeks or months. The travelling bumps are caused by the redistribution of line absorption by the velocity field of non radial oscillation ($\sim \pm$ 20 km/s): due to the different Doppler shifts of the various forwards and backwards sectors on the stellar disk some parts of the line profile cumulate absorption while others do not, which thus produces the observed bumps. The high rotation is necessary for the visibility because it resolves the structure of the moving sectors on the stellar disk.

Fast rotation appears necessary, not only for the visibility of non radial pulsations, but also for the physical existence of stable non radial oscillations (cf. Baade and Ferlet, 1984). This is well illustrated, as discussed by these last authors, in the comparison of the cases of the slowly rotating star ρ Leo (B1Ib, $v_{\sin i}$ = 70 km/s) and of the rapidly rotating star γ Arae (B1Ib, $v_{\sin i}$ = 230 km/s). For ρ Leo, Smith and Ebbets (1981) found no periodic variations in the line profiles, but event-like distorsion on a time scale of 3 hours. They suggested multimode non radial pulsations, and explained the episodic character of the line profile through destructive interferences between various modes. They noticed an increase of the Hα emission, which is a signature of mass ejection, during the phases of disturbed lines (cf. discussion in § 5). At the opposite, the study of the line profile of Si III λ 4552 in the fast rotating star γ Arae by Baade and Ferlet (1984) provides a convincing evidence of stable non radial pulsations in an early-type supergiant. These authors found two stable periods of non radial pulsations P_1 = 0.87 d and P_2 = 0.17 d, identified as corresponding to two sectorial modes (ℓ,m) = (2, -2) and (10, -10).

The opposite and very illustrative examples of ρ Leo and γ Arae are not unique. Further works by Baade (1984b) also showed the existence of two pulsation modes for the rapidly rotating star HR 3090 (B0.5Ib, $v_{\sin i}$ = 238 km/s), while for several narrower lined stars only variable line cores were found. Let us finally emphasize the problem of the persistent (blue or red) line asymmetries, found for example by Baade (1984b) in 50% of the supergiants. How should it be interpreted: as non radial pulsations with asymmetric waves or as convective motions, or as something else?

In summary we can say that there are very convincing evidences of non radial oscillations for the early type supergiants, while for late supergiants the evidences are less certain. We cannot exclude that later than some spectral type (in the F region) the supergiants pulsate radially.

3. THEORETICAL STATUS OF SUPERGIANT PULSATIONS

Regarding the question why the pulsations are more pronounced in fast rotators we may refer to the expression given by Ledoux (1959) and which links the pulsation frequency σ af a star rotating with an angular velocity Ω to the frequency σ_o of a non-rotating star: $\sigma = \sigma_o + m\, C\, \Omega$ ($m = -\ell, ...o, ...+\ell$) where C (< 1) depends on the pulsation mode. In case of zero, or of slow rotation, all the ($2\ \ell+1$) modes have nearly the same frequency, and any mechanism exciting one mode also excites the other ones. Thus, the pulsation amplitude is limited by the sharing of the pulsation energy among the ($2\ \ell+1$) modes (cf. Dziembowski, 1980). In case of fast rotation, degeneracy is lifted and the frequency intervals are enlarged. Thus, a given mode may have a large amplitude; as shown by Hansen et al. (1978), rotation preferably destabilizes prograde sectorial modes. The resonant coupling of various modes has been discussed by Baade and Ferlet (1984) and Baade (1984a); they show that the best case for a constructive and stable resonance to be created occurs when the ratio of the orders of the two-resonant mode is 5. This well corresponds to the case of the fast rotating star γ Arae, as seen above. The absence of stable resonant periods in low rotating stars results, according to Baade and Ferlet, from the rapid damping of non radial pulsations by interferences, which then lead to chaotic motions, shocks and intermittent mass ejections as in the case of ρ Leo seen above.

Let us now turn to the difficult question of the driving mechanism of supergiant pulsations; this field is yet largely unexplored, but a few propostions have been made. Firstly, we note that the excitation of pulsations by the helium ionization zones seems very insufficient to sustain the pulsations (cf. Lucy, 1976; Cox, 1983). Another process, the so-called "jolt mechanism", was proposed by Cox (1983). This idea, which is very interesting because it involves a process different from the usual ε and κ mechanisms, is that intermittent overshooting from convective cores may cause sudden mixing. This in turn leads to a pressure readjustment, it produces a small expansion of the envelope, which recollapses and then induces enhanced overshooting; and the process goes on. By studying non radial pulsation in a supergiant model, Cox (1983) found that the g_8 mode precisely has a large amplitude in the region of the steep μ-gradient which could promote some mixing there. According to Cox (1985) the jolt mechanism may produce mixing, but its ability to drive pulsations is uncertain.

The possible role of convection in the pulsations of supergiants of various spectral types was emphasized by Maeder (1980): instead of being limited to red stars as is usually the case, deep external convective zones are likely to also exist in G, F, A and even B supergiants. This is a consequence of the destabilizing effect of high radiation pressure on convection. I made the suggestion that non radial g-modes would be excited in the external convective zones of supergiants and would become periodic due to rotation as studied by Ledoux (1967). The high turbulent pressure expected in the large external convective envelopes may play a leading role in the instabilities of the extreme supergiants, the so-called Hubble-Sandage or S Doradus variables (cf. de Jager, 1984). In the outer layers of these stars the gradient of turbulent pressure may create an outwards directed acceleration, which in extreme cases (let us call it de Jager's limit) makes the external layers unbound and leads to an extreme mass loss ($\sim 10^{-3}\ M_{\odot}y^{-1}$). According to de Jager, the limit where the resultant acceleration at the surface is zero well corresponds to the upper limit of supergiant distribution in the HR diagram, as studied by Humphreys (1984).

Another very promising instability mechanism of radiative origin, the mass loss instability, has recently been proposed by Appenzeller (1986). The basic general idea is that the stellar wind and the associated instabilities will grow if an increase in the wind increases the driving radiative acceleration g_{rad}. As discussed by Appenzeller such an unstable situation occurs when, due to opacity effects, g_{rad} increases with T_{eff} less rapidly than T_{eff}^4. Although this mechanism has been proposed for the Hubble-Sandage variables, its generality and interest make it a very attractive driving mechanism to be investigated in the context of supergiant pulsations.

Let us conclude in saying that for now the relative importance of the various mentioned driving mechanisms is very uncertain. My personal guess is that radiative mechanisms are likely to dominate in early supergiants, while convective and turbulent effects may play the leading role in yellow and red supergiants.

REFERENCES

Abt, H.A., 1957, Astrophys. J. 126, 138

Appenzeller, I., 1986, in Luminous Stars and Associations in Galaxies. IAU Symp. 116, Eds. C. de Loore and A.J. Willis, in press

Baade, D., 1984a, Astron. Astrophys. 135, 101

Baade, D., 1984b, in 25th Liège Colloquium, Eds. A. Noels and M. Gabriel, p. 115

Baade, D., Ferlet, R., 1984, Astron. Astrophys. 140, 72

Boury, A., Ledoux, P., 1965, Ann. Astrophys. 28, 353

Burki, G., 1978, Astron. Astrophys. 65, 357

Burki, G., Rufener, F., Mayor, M., 1980, Astron. Astrophys. Suppl. 42, 383

Conti, P., 1982, in WR Stars: Observations, Physics, Evolution. IAU Symp. 99, Eds. C. de Loore, A. Willis; Reidel, Dordrecht, p. 3

Costero, R., Doazan, V., Stalio, R., Thomas, R.N., 1981, in Effects of Mass Loss on Stellar Evolution, IAU Coll. 59, Eds. C. Chiosi, R. Stalio; Reidel, Dordrecht, p. 131

Cox, A.N., 1983, in Astrophysical Processes in Upper MS Stars, 13th Saas-Fee Course, Eds. B. Hauck, A. Maeder, Geneva Obs., p. 1

Cox, A.N., 1985, private communication

Dziembowski, W., 1980, Lecture Notes in Physics 125, 22

https://doi.org/10.1017/S1539299600006547 Published online by Cambridge University Press

Ebbets, D., 1982, Astrophys. J. Suppl. 48, 398
Fernie, J.D., 1981, Astrophys. J. 243, 576
Fernie, J.D., 1983, Astrophys. J. 265, 999
Ferro, A.A., 1985, Mon.Not. R. Astr. Soc. 216, 571
van Genderen, A.M., 1980, Astron. Astrophys. 88, 77
van Genderen, A.M., 1985, Astron. Astrophys. 151, 349
van Genderen, A.M., 1986, Astron. Astrophys., in press
Hansen, C.J., Cox, J.P., Carroll, B.W., 1978, Astrophys. J. 226, 210
Heck, A., Burki, G., Bianchi, L., Cassatella, A., Clavel, J., 1980, Mon. Not. R. Astr. Soc. 192, 59P
Humphreys, R., 1984, in Observational Tests of the Stellar Evolution Theory, IAU Symp. 105, Eds. A. Maeder and A. Renzini, Reidel, Dordrecht, p. 279
de Jager, C., 1980, The Brightest Stars, Reidel, Dordrecht, p. 340
de Jager, C., 1984, Astron. Astrophys. 138, 246
Kirbiyik, H., Bertelli, G., Chiosi, C., 1984, in 25th Liège Colloquium, Eds. A. Noels and M. Gabriel, p. 126
Lamers, H., Stalio, R., Kondo, Y., 1978, Astrophys. J. 223, 207
Lamontagne, R., Moffat, A.F.J., 1986, Astron. Astrophys., in press
Ledoux, P., 1951, Astrophys. J. 114, 373
Ledoux, P., 1967, in The Magnetic and Related Stars, Ed. R.C. Cameron, Mono Books Corp., Baltimore, p. 65
Lovy, D., Maeder, A., Noels, A., Gabriel, M., 1984, Astron. Astrophys. 133, 307
Lucy, L.B., 1976, Astrophys. J. 206, 499
Maeder, A., 1980, Astron. Astrophys. 90, 311
Maeder, A., 1981, Astron. Astrophys. 102, 401
Maeder, A., 1985, Astron. Astrophys. 147, 300
Maeder, A., Rufener, F., 1972, Astron. Astrophys. 20, 437
Moffat, A.F.J., 1974, Astron. Astrophys. 32, 435
Moffat, A.F.J., 1982, in WR Stars: Observations, Physics and Evolution, IAU Symp. 99, Eds. C. de Loore and A.J. Willis, Reidel, Dordrecht, p. 263
Noels, A., Gabriel, M., 1981, Astron. Astrophys. 101, 215
Noels, A., Magain, E., 1984, Astron. Astrophys. 139, 341
Noels, A., Maserel, C., 1982, Astron. Astrophys. 105, 293
Noels, A., Scuflaire, R., 1986, Astron. Astrophys., in press
Pauldrach, A., Puls, J., Hummer, D.G., Kudritzki, R.P., 1985, Astron. Astrophys. 148, L1-4
Pauldrach, A., Puls, J., Kudritzki, R.P., 1985, Astron. Astrophys., in press
Percy, J.R., Welch, D.L., 1983, Publ. Astron. Soc. Pacific 95, 491
Simon, R., 1957, Bull. Acad. Roy. Belgique, Cl. Sci. 43, 610
Simon, N.R., Stothers, R., 1969, Astrophys. J. 155, 247
Simon, N.R., Stothers, R., 1970, Astron. Astrophys. 6, 183
Smith, M.A., 1981, in Proc. Worksh. Puls. B Stars, Ed. C. Sterken, Obs. Nice, p. 317

Smith, M.A., Ebbets, D., 1981, Astrophys. J. 247, 158
Sterken, C., 1977, Astron. Astrophys. 57, 361
Sterken, C., 1981, in The Most Massive Stars, ESO Workshop, p. 147
Vogt, S.S., Penrod, G.D., 1983, Astrophys. J. 275, 661
Vreux, J.M., 1985, Publ. Astron. Soc. Pac., 97, 274
Vreux, J.M., Andrillat, Y., Gosset, E., 1985, Astron. Astrophys. 149, 337
Weller, W.G., Jeffers, S., 1979, in Mass Loss and Evolution of O-type Stars, IAU Symp. 83, Eds. P. Conti, C. de Loore; Reidel, Dordrecht, p. 27