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Pulsations in red supergiants with high L/M ratio

Implications for the stellar and circumstellar structure of supernova progenitors

A.Heger[1,2], **L. Jeannin**[3], **N. Langer**[1,4], **and I. Baraffe**[3]

[1] Max-Planck-Institut für Astrophysik, D-85740 Garching, Germany
[2] UCO/LICK Observatory, University of California, Santa Cruz, CA 95064, U.S.A.
[3] Centre de Recherche Astronomique de Lyon (UMR 5574, CNRS), Ecole Normale Supérieure de Lyon, 46 allée d'Italie, F-69364 Lyon Cedex 07, France
[4] Institut für Theoretische Physik und Astrophysik, Universität Potsdam, D-14415 Potsdam, Germany

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Abstract. We investigate the pulsational properties of RSG models — which we evolve from ZAMS masses in the range 10 to $20\,\mathrm{M}_\odot$ — by means of linear and non-linear calculations. We find period and growth rate of the dominant fundamental mode to increase with increasing luminosity-to-mass ratio L/M. Our models obtain relatively large L/M values due to the inclusion of rotation in the evolutionary calculations; however, the largest values are obtained at and beyond central He-exhaustion due to major internal rearrangements of the nuclear burning regions. Our non-linear calculations as well as the behavior of the linear period and growth rate of the pulsations for periods approaching the Kelvin-Helmholtz time scale of the H-rich stellar envelope point towards the possibility of large amplitude pulsations. Such properties are similar to that found in AGB stars and suggest the possibility of a "superwind" to occur before the RSGs explode as supernovae. We conclude that changes in global stellar properties during the last few 10^4 yr before core collapse may lead to drastic changes in the pulsational and wind properties of pre-supernova stars, with marked consequences for the immediate pre-supernova structure of the star and the circumstellar medium. We compare our results with observations of long-period OH/IR variables and discuss observational evidence for our scenario from observed supernova light curves, spectra and remnants.

Key words: stars: massive – stars: pulsation – OH/IR – long period variables – supernovae the

Send offprint requests to: A. Heger (*ahg@mpa-garching.mpg.de*)

1. Introduction

Massive stars, which develop a collapsing iron core at the end of their evolution, are the main agents of nucleosynthesis and chemical evolution in the Milkyway and other galaxies (cf. Timmes et al. 1995). According to the standard picture, based on stellar evolution calculations (e.g. Schaller et al. 1992) and on the interpretation of Type II supernova light curves (Eastman et al. 1994), most pre-supernova stars are red supergiants (RSG) with massive H-rich envelopes. In the present paper, we focus on a property of the structure of the majority of pre-supernova stars which is usually neglected: they are pulsationally unstable. In particular, we suggest the possibility for this instability to become violent several 10^4 yr before the supernova explosion, with prominent consequences for the envelope structure of the exploding star as well as the distribution of the circumstellar matter at the time of the supernova event.

Observations of long-period variables (LPV) in the Galaxy and particularly in the Magellanic Clouds (Wood et al. 1983, 1992; Whitelock et al. 1994) reveal two distinct groups of pulsating cool stars: intermediate mass stars on the Asymptotic Giant Branch (AGB) with zero-age main-sequence (ZAMS) masses $M_{\mathrm{ZAMS}} \lesssim 8\,\mathrm{M}_\odot$, and RSGs, massive stars with $M_{\mathrm{ZAMS}} \gtrsim 8\,\mathrm{M}_\odot$. While the periods of the visible LPVs are generally shorter than 1000 days, longer periods are found in OH/IR sources (Engels et al. 1983; Le Bertre 1993; Jones et al. 1994). Most of the OH/IR sources seem to lie on the period-luminosity relation observed for AGB stars (Whitelock et al. 1991; Feast et al. 1989; Groenewegen and Whitelock 1996). Interestingly enough, some of them show bolometric luminosities much higher than expected for Miras. One may thus attempt to associate these sources with RSGs. However, known pulsating RSGs show generally small amplitudes whereas the long period OH/IR sources are usually associated to high amplitudes, as expected for AGB stars (cf. Wood et al. 1992). Therefore, it is puzzling that the most luminous OH/IR-sources found by Le Bertre (1993) show in fact very large amplitudes.

Recently, a theoretical analysis of RSG evolution and pulsation in the Large Magellanic Cloud (LMC) has been performed by Li and Gong (1994). By coupling linear stability analysis and evolutionary models, they could follow the evolution of stars from 15 to $30\,\mathrm{M}_{\odot}$ in the period-luminosity diagram. They concluded that RSG models can reproduce the observed period-luminosity (P-L) relationship of LPVs in the LMC, which is, however, on the RSG branch restricted to periods below ~ 900 days.

In the present paper, we reinvestigate the pulsational properties of RSG models. We compute stellar evolutionary models for massive stars which evolve into RSGs, and then analyze their linear pulsation properties. We are using a hydrodynamic stellar evolution code which allows us to also compute models in the non-linear regime of the pulsations. Furthermore, we included the physical effects of stellar rotation on the evolution, which results in a remarkable increase of the L/M ratio of our models already on the main sequence. More dramatically, the L/M ratio increases at and beyond central helium exhaustion, as it also does for non-rotating stars. We show that this property leads to a strong increase of the growth rate of the fundamental mode, which may have considerable consequences for the pre-supernova structure of the stars and of the circumstellar matter. We compare our results with recent observations of luminous OH/IR sources and with supernova observations.

2. Stellar evolutionary models

The stellar evolution calculations presented here are obtained with an implicit hydrodynamic stellar evolution code (cf. Langer et al. 1988). Convection according to the Ledoux criterion and semiconvection are treated according to Langer et al. (1983), using a mixing length parameter $\alpha_{\mathrm{MLT}} = 1.5$ and semiconvective mixing parameter of $\alpha_{\mathrm{sem}} = 0.04$ (Langer 1991). Opacities are taken from Alexander and Fergusson (1994) for the low temperature regime, and from Iglesias and Rogers (1996) for higher temperatures. A parameterization of the mass loss rate according to Nieuwenhuijzen and de Jager (1990) is adopted.

During the last decade, the evidence that rotation and rotationally induced mixing in particular affects the evolution of massive main sequence stars has grown substantially (cf. Fliegner et al. 1996, and references therein). In the present calculations, effects of rotation on the stellar structure as well as rotationally induced mixing processes are included in a way similar to Pinsonneault et al. (1989). The main effect of rotation in relation to the pulsational properties of the RSGs is an increase of the mass of the He-core, as well as an enrichment of the envelope with products of central H-burning. Both effects are qualitatively discussed in Langer et al. (1997). Note that the latter in particular leads to agreement with the surface abundance pattern observed in OB main-sequence stars (cf. Fliegner et al. 1996). The main effect of the increased core masses is a larger luminosity during the advanced evolution, an effect which is produced similarly by efficient convective core overshooting (e.g., Stothers and Chin 1992). The dynamical effect of rotation on the structure is found to be negligible and does not affect the pulsational properties of our RSG models. The ratio of rotation velocity to the critical value at the surface is below $\sim 0.3\,\%$ for all RSG models considered.

We compute four evolutionary sequences for different ZAMS masses, 10, 12, 15 and $20\,\mathrm{M}_{\odot}$, with an initial composition of $Y = 0.28$ and $Z = 0.02$ (cf. Table 1). We adopt an initial equatorial rotation velocity of about $200\,\mathrm{km\,s^{-1}}$, which is a typical value for these stars (Fukuda, 1982; Howarth et al., 1997) and corresponds to $\sim 35\,\%$ of their critical rotation speed. We start the stellar evolution with a fully convective, rigidly rotating model on the pre-main sequence, and we follow it beyond central neon exhaustion so that the stellar envelope can safely be considered to be in the pre-supernova state. The evolutionary tracks of our models in the Hertzsprung-Russell diagram (HRD) are shown in Fig. 1, starting at H-ignition.

Table 1. Time-scales of hydrogen burning, helium burning, and life time at $T_{\mathrm{eff}} < 5000\,\mathrm{K}$. Furthermore, properties of the last computed model of each sequence are given (cf. Fig. 1): surface helium mass fraction, luminosity, effective temperature, radius, final stellar mass, He- and C/O-core mass and Kelvin-Helmholtz time scale of the H-rich envelope

ZAMS mass / $\mathrm{M}_{\odot}$	10	12	15	20
$\tau_{\mathrm{H}}/10^6$ yr	25.5	18.9	13.8	9.6
$\tau_{\mathrm{He}}/10^6$ yr	2.86	1.99	1.22	0.64
$\tau_{\mathrm{red}}/10^6$ yr	0.39	0.46	1.23	0.66
Y_{s}	0.39	0.40	0.42	0.45
$\log(L/\mathrm{L}_{\odot})$	4.66	4.86	5.05	5.36
$T_{\mathrm{eff}}/\mathrm{K}$	3203	3152	3107	3164
$R/\mathrm{R}_{\odot}$	702	903	1161	1614
$M/\mathrm{M}_{\odot}$	9.2	10.4	10.9	11.0
$M_{\mathrm{He}}/\mathrm{M}_{\odot}$	2.8	3.6	5.1	7.7
$M_{\mathrm{C/O}}/\mathrm{M}_{\odot}$	1.8	2.3	3.4	4.6
$\tau_{\mathrm{KH}}/\mathrm{yr}$	28.7	17.1	7.7	1.5

The tracks presented in Fig. 1 are qualitatively similar to those obtained by previous calculations including overshooting (Schaller et al. 1992, Stothers and Chin 1992). The total mass lost by our stars is dominated by RSG

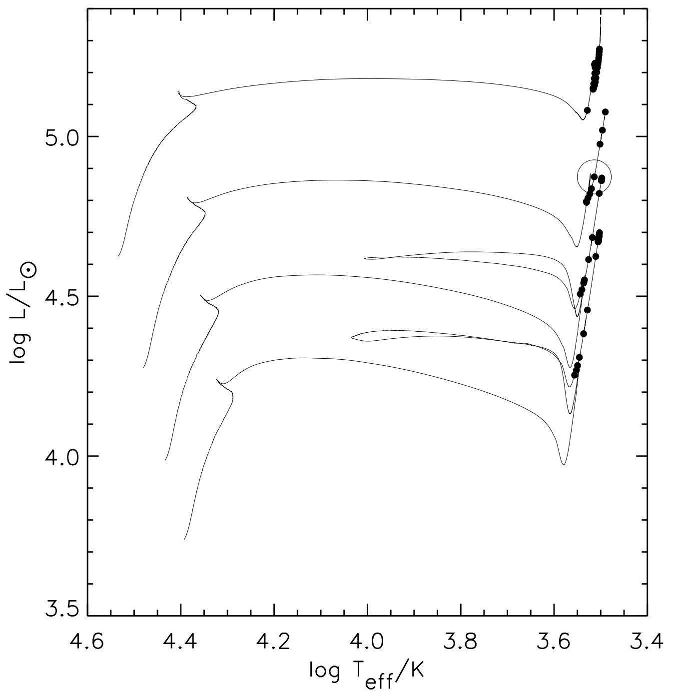

Fig. 1. Evolutionary tracks of the 10, 12, 15 and 20 $M_\odot$ sequences from the ZAMS to central neon exhaustion. Models for which a linear pulsation analysis has been performed (cf. Sect. 3) are marked by dots. The circle marks the initial model investigated in Sect. 4; cf. Figs. 3 and 5.

winds. Due to a slightly larger luminosity during central He-burning compared to the tracks of Schaller et al. (1992), we obtain somewhat smaller final masses (cf. Table 1); they are comparable to those obtained by Meynet et al. (1994). The effect of rotation on the final L/M ratio can be summarized as follows: it results in an increase of the luminosity due to a larger He-core, and the correspondingly higher mass loss rate yields a smaller final mass; both properties translate into a higher L/M value, which is a key parameter for the pulsations (cf. Sect. 3).

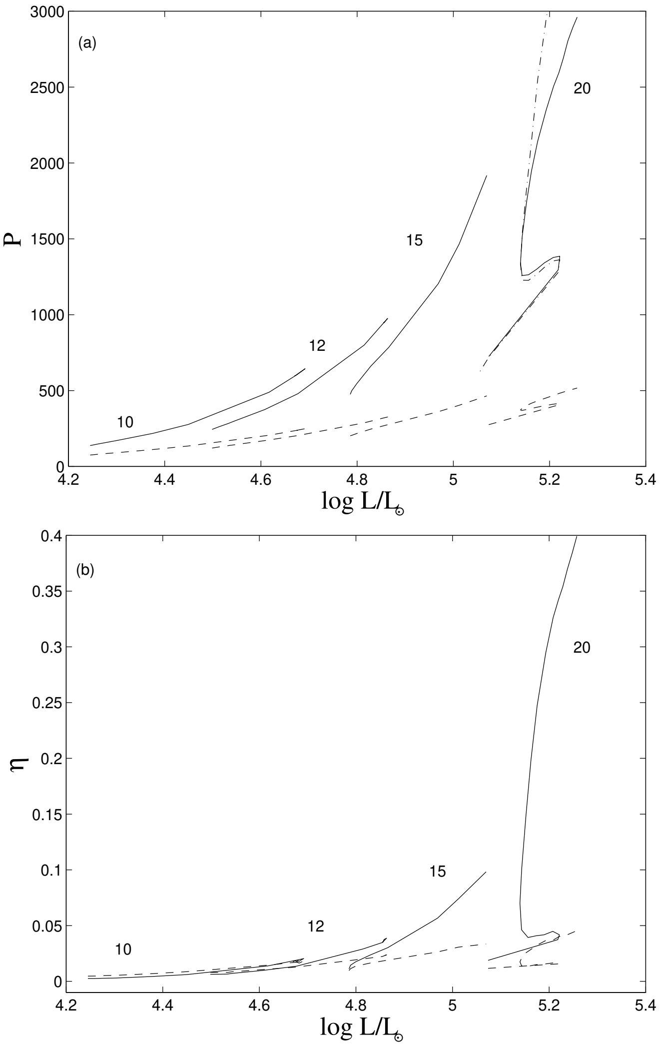

Fig. 2. Period in days (**a**) and growth rate (**b**) of the pulsations found in the stellar models of the 10, 12, 15 and 20 $M_\odot$ sequences marked in Fig. 1. The full drawn lines correspond to the fundamental mode, the dashed lines to the first overtone. The dash-dotted line in (a) corresponds to the adiabatic period of the 20 $M_\odot$ sequence.

3. Linear stability analysis

We perform a linear non-adiabatic stability analysis of the RSG models marked by dots in Fig. 1. For the two lower-mass sequences (10 and 12 $M_\odot$), the stability analysis is started after they returned from their blue loop (cf. Fig. 1) near the end of central He-burning. For the 15 (20) $M_\odot$ models, the analysis begins at a central helium mass fraction of 0.43 (0.97). The radial pulsation code used for this study is described in Jeannin et al. (1996). Our analysis is based on complete stellar models i.e. the whole stellar structure from the center to the surface is taken into account. The convective flux is assumed to be frozen in for the stability analysis (cf. Sect. 4).

The linear pulsation code assumes that the stellar models are in complete thermal and hydrostatic equilibrium. Although the evolutionary models include rotation and slightly depart from thermal equilibrium, we have checked the consistency of this approximation. Rotation has no dynamical effect on the RSG pulsations. As the stellar envelope expands when the star becomes a RSG it spins down dramatically. Furthermore, as the oscillations take place only in the envelope, they are not affected by the rotation of the helium core. For each model at a given mass, L and $T_{\rm eff}$, we construct static envelope models with the same input physics (opacity, mixing length, composition). The pulsation properties of the envelopes are then compared to those of the corresponding evolu-

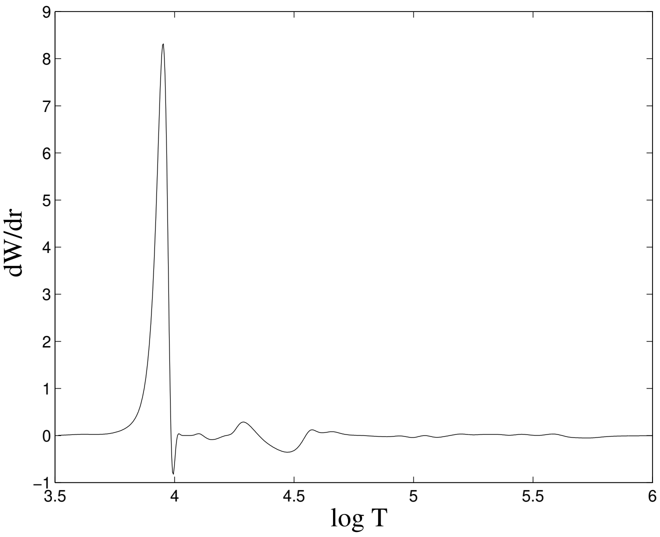

Fig. 3. Differential work (in arbitrary units) as a function of temperature for a model of the 15 $\mathrm{M}_\odot$ sequence characterized by $\log L/\mathrm{L}_\odot = 4.89$, $T_{\mathrm{eff}} = 3260\,\mathrm{K}$ and $M \simeq 11\,\mathrm{M}_\odot$, and indicated by a circle in Fig. 1. Excitation zones correspond to dW/dr > 0.

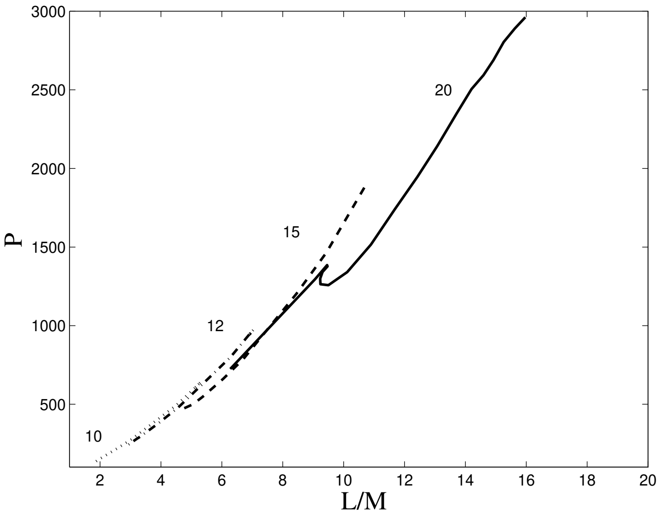

Fig. 4. Period of the fundamental mode (in days) as a function of the ratio (L/M) (in units of $10^3\,\mathrm{L}_\odot/\mathrm{M}_\odot$). The different curves correspond to different ZAMS masses as indicated.

tionary model. In all cases, the differences are less than 5 % for the period. The analysis was stopped for the brightest models, when the decreasing evolutionary time scale starts to invalidate our approximation.

The periods P and relative growth rates η (defined as minus the ratio of the imaginary part of the eigenfrequency σ to its real part, adopting a time dependence of the form $\exp(i\sigma t)$) of the two lowest-order modes of the four stellar sequences are displayed in Fig. 2. Typical values of the period for the fundamental mode range between 200 and 3000 days. The periods found for the first overtone do not exceed 500 days in any case. Both modes are unstable ($\eta > 0$) for all investigated models, and the growth rates increase with luminosity for a given ZAMS mass. The higher the ZAMS mass, the higher the maximum value of the growth rate reached. The growth rate derived for the fundamental mode is always larger than that of the first overtone. The latter remains systematically smaller than 0.05, whereas a maximum value of 0.4 for the fundamental mode is obtained in the $20\,\mathrm{M}_\odot$ case. For the $15\,\mathrm{M}_\odot$ model, the fundamental mode growth rate increases from ~ 0.01 to ~ 0.1. It remains smaller than 0.04 for the 10 and $12\,\mathrm{M}_\odot$ stars (cf. Fig. 2).

The excitation mechanism appears to be related to the traditional κ mechanism as indicated by the work integral W of the models. The driving of the pulsation is essentially provided in the hydrogen ionization zone. This is illustrated in Fig. 3 where dW/dr is displayed as a function of temperature for a model of the 15 $\mathrm{M}_\odot$ sequence at the end of central He-burning.

The large value of the periods and growth rates mentioned above can be related to the large L/M values obtained from the evolutionary calculations. This behavior is illustrated in Fig. 4 which shows the variation of P with L/M for the four investigated sequences. The variation $P \propto L/M$ is connected to the properties of convective pulsating *envelopes* which obey a period-radius relation $P \propto R^2/M$ rather than the canonical $P \propto R^{3/2}/M^{1/2}$. This has been shown analytically by Gough et al. (1965) for polytropic envelopes of index $n = 3/2$ corresponding to a fully convective structure. Since the effective temperature varies hardly on the RSG branch, the variation $P \propto R^2/M$ is equivalent to $P \propto L/M$.

The relevant quantity for the growth or decay of pulsations, connected to the growth rate, is the Kelvin-Helmholtz or thermal time scale of the H-rich envelope $\tau_{\mathrm{KH}} \propto M M_{\mathrm{env}}/LR$. It governs the degree of non-adiabaticity in the envelope and thus the heat exchange with the pulsation. In our case, τ_{KH} decreases as the models get brighter (and lose mass), and for the brightest models τ_{KH} becomes very close to the fundamental period (cf. Fig. 7 below). Non-adiabatic effects are thus important and are responsible for the high values of the growth rates found as the luminosity increases and τ_{KH} decreases (see also Ostlie and Cox, 1986).

The large fundamental to first overtone period ratio P_0/P_1 displayed by the models in Fig. 2 can be directly related to the internal structure of the stars. With increasing luminosity, the star tends toward a dynamically unstable configuration with the mean value of the adiabatic exponent $\Gamma_1 \sim 4/3$. In this case, the solution of the linear adiabatic wave equation (cf. Cox 1980) shows that the square of the adiabatic pulsation frequency becomes negative and the adiabatic period becomes mathematically infinite. The divergence of the adiabatic period for the fundamental mode is illustrated in Fig. 2a for the $20\,\mathrm{M}_\odot$ sequence. As long as the non-adiabatic effects remain small, the non-adiabatic period is rather close to the adiabatic value and follows the same behavior. When the non-adiabatic effects become strong however, the non-adiabatic period start to depart from the adiabatic solution (cf. Fig. 2a).

4. Non-linear computation of the pulsations

As mentioned above, the stellar evolution models are computed with a hydrodynamic code, which is therefore able to follow instabilities on dynamical time scale. Usually, those are not found due to the large evolutionary time step compared to the dynamical time scale of the star. However, during the late nuclear burning phases (C- and Ne-burning), nucleosynthesis imposes an extremely small time step comparable to or even smaller than the dynamical time scale. I.e., only the combination of hydrodynamic stellar evolution calculations of mass losing RSGs in late nuclear burning stages enabled us to find the strong instability described here,

Fig. 5 displays, in the HRD, the growth of the pulsational instability of a model of the $15\,\mathrm{M}_\odot$ sequence at the end of central He-burning (0.2 % helium left in the center). The initial model for the non-linear pulsation analysis, indicated by a circle in Fig. 1, is characterized by $\log L/\mathrm{L}_\odot = 4.89$, $T_\mathrm{eff} = 3260\,\mathrm{K}$ and $M \simeq 11\,\mathrm{M}_\odot$. The first 50 pulsation cycles give a period P $\simeq$ 800 days and an estimated growth rate $\eta = 0.033$, corresponding to the fractional increase of the radius amplitude per pulsation cycle. These values are in excellent agreement with those found for the fundamental mode by the linear stability analysis performed on the equilibrium model ($P_0 = 802$ days and $\eta_0 = 0.033$). Fig. 5 shows that after 75 cycles, the luminosity amplitude has already grown to a factor of two, i.e. to 0.75 mag in M_bol.

Our non-linear calculations are limited for two reasons. The first is that our code is fully implicit and therefore subject to strong numerical damping (cf. Appenzeller 1970). Thus, we are not able to detect the pulsations predicted by the linear theory (Sect. 3) for the case of small growth rates (e.g. for the $10\,\mathrm{M}_\odot$ sequence). Secondly, we are limited on the other extreme to not too large amplitudes, since our code is not set up to deal with shock waves. For this reason we did stop the calculation shown in Fig. 5 when the surface velocity reached about $10\,\mathrm{km\,s}^{-1}$, and we did not attempt to compute non-linear pulsations for increasing amplitudes.

The main uncertainty in the description of the pulsational behavior of our models is certainly due to the unknown feedback of convection. As in Miras, the convective and the pulsation time scale are comparable, and at present no solution to the coupled problem exists (cf. Gautschy & Saio 1995). In contrast to the linear stability analysis presented in Sect. 3, where the convective flux is frozen in, it is assumed to adjust instantaneously in the hydrodynamic stellar evolution code. Both treatments thus represent simple but different possibilities to deal with the convective flux feedback and give essentially the same periods and growth rates. Even within a "phase-lag" approach (Arnett 1969) to describe time-dependent convection, Langer (1971) has shown that the general pulsation properties (period, growth rate) derived from linear stability analysis do not depend strongly on the phase-lag parameters. However, the growth rates derived in the present work, as they depend on the energy transport, should only be taken as indicative. A physically correct treatment of thermal and dynamical coupling of convection and pulsation — which is not yet available — may be necessary to predict them reliably. We can be more confident on the values of the period, which essentially depend on the structure and the sound speed in the envelope.

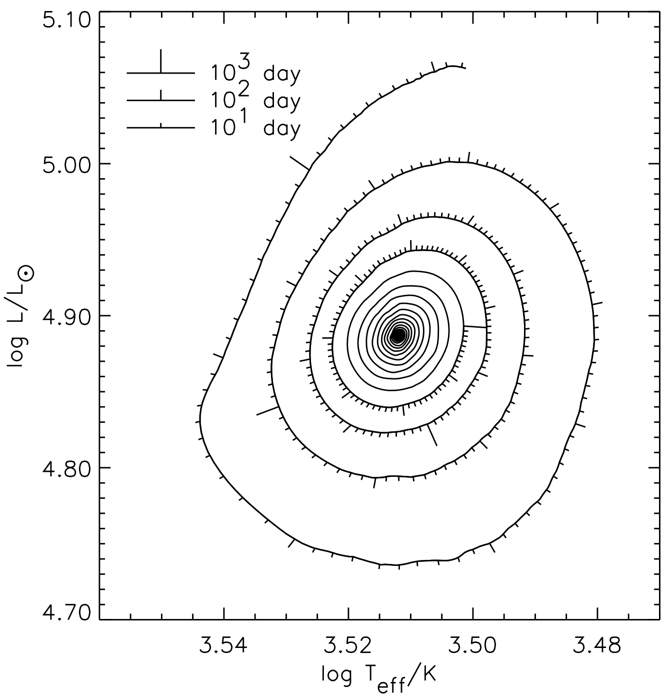

Fig. 5. Growing pulsational instability of a $\sim 11\,\mathrm{M}_\odot$ RSG model (evolved from a $15\,\mathrm{M}_\odot$ ZAMS star) at the end of central He-burning, traced by our stellar evolution code. The period of the oscillation is about 800 days, the Kelvin-Helmholtz time scale of the stellar envelope is roughly 30 yr. About 75 pulsation cycles have been followed.

The results of the present analysis and the fate of the star thus remain uncertain, since we ignore the effects of convection on the pulsational driving. Nevertheless, the example shown in Fig. 5 and the similarity of the pulsational properties (linear and non-linear) discussed above with those obtained for AGB stars, in particular the huge increase in period and growth rate during the final evolutionary stages, may suggest the possibility of pulsations of large amplitude in RSGs in connection with a strong increase in the mass loss rate, i.e. a "superwind" phase as that observed for Miras and expected for the terminal AGB evolution. This will be discussed in the next Section.

5. Discussion

Fig. 6 shows the *P*-*L* relation derived from our models in comparison to observations of long period OH/IR sources from Engels et al. (1983), Le Bertre (1991, 1993) and Jones et al. (1994). The mean *P*-*L* relation observed for O-rich Miras (Feast et al. 1989) is also shown. Though most of the OH/IR sources follow the latter *P*-*L* relationship and may thus be identified as AGB stars, some objects, mostly from Le Bertre (1993), are overluminous and fall on the curves of our RSG models. Note that the narrow relation between the period and the L/M-ratio found in Fig. 4 might provide an interesting tool to deduce actual masses of these sources.

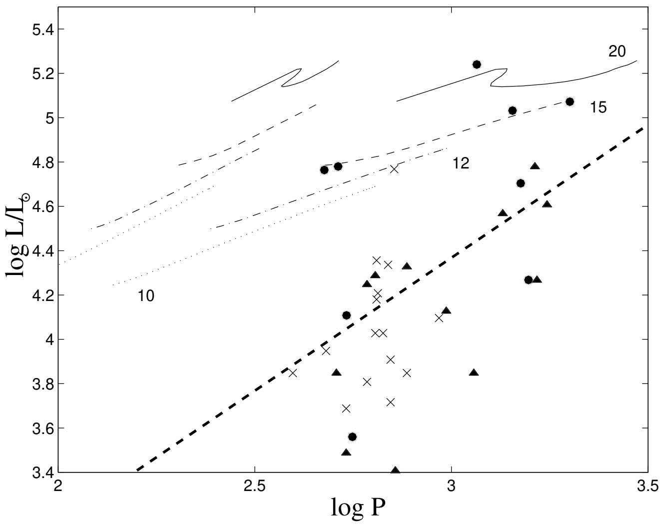

Fig. 6. Evolution of the luminosity as a function of the period (in days) for RSG models along the different calculated tracks, for the fundamental mode (right curves) and the first overtone (left curves). The ZAMS masses are indicated for the fundamental periods: $10\,M_\odot$ (dot), $12\,M_\odot$ (dash-dot), $15\,M_\odot$ (dash) and $20\,M_\odot$ (solid line). The thick dashed line corresponds to the relationship observed for O-rich Miras (Feast et al. 1989). Observations of OH/IR sources are from: Engels et al. (1983, triangles), Le Bertre (1991, 1993, full circles) and Jones et al. (1994, crosses).

Although the overluminous sources show large amplitudes (1 to 3 mag), a feature which is generally attributed to AGB stars, the RSG nature of at least some of them appears to be consistent with our results, which suggests that RSGs may also be able to develop large amplitude pulsations. Most of the overluminous OH/IR sources show extremely strong mass loss from the central object, with rates as high as $10^{-4}\,M_\odot\,yr^{-1}$ (Le Bertre 1991). This is in support of the idea of high mass loss in connection with large periods, growth rates and amplitudes. The order of magnitude of the observed mass loss rates is similar to what is discussed for the final AGB "superwind" (Vassiliadis and Wood 1993); however, note that Le Bertre's sources are oxygen-rich while the classical AGB superwind is expected in carbon-rich sources.

Fig. 7 shows that very large pulsation periods and consequently large amplitudes and mass loss rates may be expected to occur at and beyond central helium exhaustion for our model sequences, over a time scale of some 10^4 yr, implying the loss of most of the hydrogen-rich envelope which remained on the star so far (cf. Table 1). In this context we emphasize the self-enhancing character of the pulsational mass loss increase since, as the envelope mass decreases, L/M is increased and the Kelvin-Helmholtz time scale of the envelope is decreased. This effect is not yet taken into account in the present calculations, where only the mass loss according to Nieuwenhuijzen and de Jager (1990) is adopted. Consequently, the superwind instability may even develop stronger than Fig. 7 may suggest.

The probability of observing RSGs in a stage of large amplitude pulsation or in a "superwind" phase is not very large (cf. Fig. 7); however, such events might have marked consequences on the appearance of the supernova explosion. Weiler et al. (1992) have found a periodic modulation of the pre-supernova mass loss from the radio light curve of SN 1979C. Although in this case the inferred period in the pre-supernova mass loss ($\sim$ 4000 yr) does not fit to dynamical pulsations discussed here, this work shows the potential of radio observations of supernovae to find evidence for those. A period of the radio signal of the order of few days would be expected in the early phase of the supernova evolution.

A "superwind" occurring some 10^4 yr before the explosion could reduce the mass of the H-rich envelope of the star to less than $1\,M_\odot$; this would make the star He-rich and hotter than a typical RSG (cf. Höflich et al. 1993). These features are reminiscent of SN 1993J, which apparently was a He-enriched K supergiant with an envelope mass of less than $\sim 0.5\,M_\odot$ (Nomoto et al. 1993, Woosley et al. 1994). The progenitor structure of this supernova is currently interpreted as a result of close binary interaction (e.g. Nomoto et al. 1993); however, no companion star could be yet found. This situation is similar to that of SN 1987A: there also, the circumstellar matter clearly indicates that the progenitor star experienced a major structural change several 10^4 yr before the supernova explosion.

Another example of a pre-supernova star which experienced the loss of most of the H-rich envelope before the explosion appears to be the progenitor of SN 1054, i.e. the progenitor of the Crab nebula. H-rich gas associated with this supernova remnant has only been found recently by Murdin (1994) in the form of an H-rich halo of several $M_\odot$ (cf., however, Fesen et al. 1997).

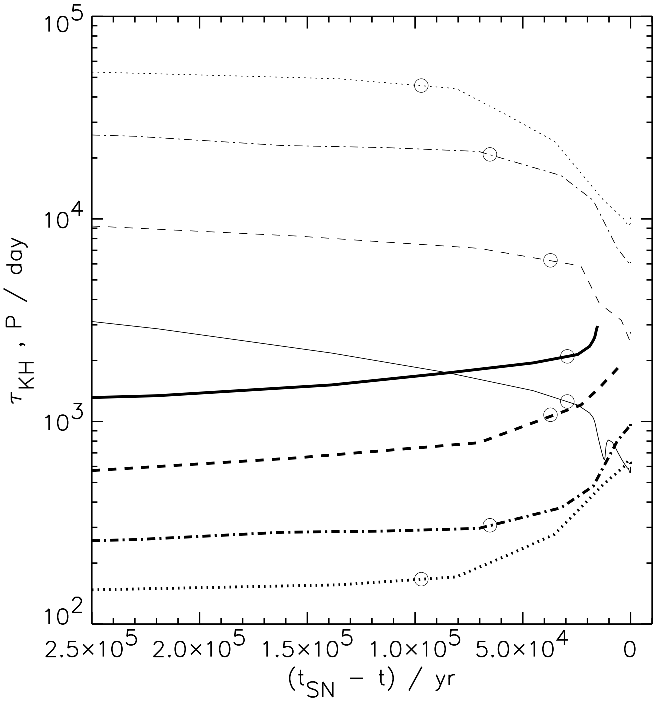

Fig. 7. Kelvin-Helmholtz time scale of the H-rich stellar envelope (thin lines) as function of the time left until the supernova explosion of the star, for the computed 10 (dot), 12 (dash-dot), 15 (dash), and 20 $M_\odot$ (solid line) sequences (cf. Fig. 1). The thick lines show the period of the fundamental mode as derived from the linear stability analysis (cf. Sect. 3). Small circles designate the time when the central helium mass fraction has reached 1%, i.e. roughly central helium exhaustion. It is evident that, at least for the 15 and 20 $M_\odot$ sequences pulsation periods of the order of the Kelvin-Helmholtz time scale occur. Note that for the last models of these two sequences pulsation periods could not be derived due to strong departures from thermal and hydrostatic equilibrium.

Tsiopa (1995) has summarized evidence from supernova spectra for the ejection of material some 10^4 yr before the explosion; she found evidence in about half a dozen cases, including the well known SN 1983K and SN 1988Z.

The scenario outlined above has also consequences for the formation of Wolf-Rayet stars. If the critical L/M value for the occurrence of strong pulsations and associated strong mass loss would occur in a RSG already during central helium burning, it would evolve into a Wolf-Rayet star. This may happen for larger initial masses as those considered by us, or for larger initial rotation rates. The transition objects may be the so called yellow hypergiants, highly variable and very luminous stars evolving off the RSG branch (Smoliński et al. 1989). Correspondingly, the minimum ZAMS mass for Wolf-Rayet star formation might be reduced below values currently found in stellar evolution calculations (i.e. $25\ldots35\,M_\odot$; cf. Schaller et al. 1992, Meynet et al. 1994), thereby increasing the number of single stars contributing to supernovae of Type Ib/c (cf. Woosley et al. 1993, Langer and Woosley, 1996).

In this context it is noteworthy that García-Segura et al. (1996), on the basis of hydrodynamic computations for the pre-supernova evolution of the circumstellar material around massive stars, concluded from the location of the quasi-stationary flocculi of the Cas A supernova remnant that the progenitor star evolved from the RSG branch into a Wolf-Rayet star roughly 10^4 yr before the supernova explosion. An increased mass loss due to pulsations during the last few 10^4 yr in the evolution of RSGs makes such a scenario even more likely.

6. Conclusions

In the present work, we analyze the pulsational properties of RSG models. Due to the inclusion of rotation in the stellar evolution calculations, our RSG models evolve to high values of L/M. Consequently, their pulsations are characterized by long periods (up to 3000 days) and large growth rates, much greater than previously found in the work of Li and Gong (1994). We thus argue that RSGs may display large amplitude pulsations like AGB stars, preferentially as OH/IR sources, and perhaps even evolve a "superwind". Due to the marked increase in the luminosity of RSGs during the last couple of 10^4 yr, such a behavior is most likely to happen during the final evolutionary phases preceding the supernova explosion. Observed properties of Type II supernovae and their remnants, and of overluminous OH/IR sources, give some support to this scenario.

More detailed and extended analysis, taking into account non-linear effects occurring at high amplitudes and the possible effects of shock waves should be performed in the future, in order to determine more precisely the amplitudes of the pulsation and to accurately estimate the region in which RSG pulsations are important for the evolution of the stars and the pre-supernova circumstellar matter.

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