TITLE: A NONLINEAR STUDY OF LUMINOUS BLUE VARIABLES AND POSSIBLE OUTBURSTS

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A Nonlinear Study of Luminous Blue Variables and Possible Outbursts

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1. Introduction

Linear pulsation analysis of luminous blue variable models shows instability to pulsations in multiple radial and nonradial strange modes (see Glatzel, these proceedings). These modes have large linear growth rates, sometimes exceeding several hundred percent per period, which prompted us to investigate the nonlinear behavior of envelope models. While the nonradial modes are predicted in the linear analysis to have higher growth rates than the radial modes, nonlinear nonradial pulsations are beyond the capabilities of pulsation hydrodynamics codes developed to date. As for relevant radial nonlinear calculations, Stothers & Chin (1993) report briefly on nonlinear hydrodynamic calculations of one dynamically unstable massive star envelope model. Aikawa & Sreenivasan (1996) have done nonlinear oscillation modeling of strange modes in low-mass AGB stars. Kiriakidis et al. (these proceedings) present nonlinear models (not including convection) of two types of strange-mode pulsators, massive stars and Wolf-Rayet stars. They find periodic or irregular pulsations, and suggest that pulsation drives mass loss. Here we present new nonlinear hydrodynamic calculations to explore the link between strange-mode pulsations and LBV outbursts.

2. Model Properties

We use the fully-implicit Lagrangian hydrodynamic pulsation code described by Ostlie (1990), Cox (1990), and Ostlie & Cox (1993) to calculate the nonlinear pulsations of massive star envelopes near the Humphreys-Davidson limit. The code has been updated to include the OPAL opacities and equation of state (Rogers & Iglesias 1992). The salient feature of the code is a time-dependent convection treatment. The time dependence of the convective velocity is determined by a weighted interpolation between the convective velocities of the past two timesteps and the instantaneous value from the mixing-length theory. Nonlocal effects are also included via a weighted average of the local convective velocity with the convective velocity of zones within one mixing length distance. As we show below, time-dependent convection proved critical to the mechanism for LBV outbursts.

We hydrodynamically analysed three sets of envelope models based on first crossing evolution models of initial mass 80 and 50 $M_\odot$ (see Cox et al., these proceedings). The first set has solar-type metallicity ($Z=0.02$), final mass 47.3 $M_\odot$, $T_{eff}=17000$ K, and log $L/L_\odot \sim 6.1$, representative of high-mass Galactic LBVs near the diagonal part of the Humphreys-Davidson Limit (e.g. P Cygni).
The second set has mass 54.9 $M_\odot$, $T_{\text{eff}}=16000$ K, $Z=0.01$, and log $L/L_\odot \sim 6.1$, representative of high-mass LMC LBVs near the HD Limit (e.g. S Dor). The third set has mass 31.1 $M_\odot$, log $L/L_\odot \sim 5.8$, $T_{\text{eff}}=12750$ K, and $Z=0.02$, representative of lower-luminosity Galactic LBVs just below the horizontal part of the H-D limit (e.g. HR Car). Within each set we investigate several surface helium abundances in $Y$ increments of 0.10. Note that for densities and temperatures typical of LBV envelope models, the opacity decreases by about 5% for $Y$ increase of 0.10. Evolution models can be made to expose material with different helium enrichments by varying the mass-loss rate; typically the model must lose 30-40% of its mass (via a wind, or episodically) to expose material significantly enriched in helium by the time it reaches the LBV instability strip.

Table 1. Luminous Blue Variable models

<table>
<thead>
<tr>
<th>Envelope Y</th>
<th>I/HP</th>
<th>Linear period (days)</th>
<th>Kinetic energy growth per period</th>
</tr>
</thead>
<tbody>
<tr>
<td>47.28 $M_\odot$, 16980 K, Z=0.02</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.38</td>
<td>1.87</td>
<td>9.5</td>
<td>0.70</td>
</tr>
<tr>
<td>0.46</td>
<td>1.87</td>
<td>10.6</td>
<td>0.40*</td>
</tr>
<tr>
<td>0.58</td>
<td>1.87</td>
<td>15.1</td>
<td>2.3*</td>
</tr>
<tr>
<td>54.9 $M_\odot$, 16000 K, Z=0.01</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.29</td>
<td>0.5</td>
<td>18.0</td>
<td>0.40</td>
</tr>
<tr>
<td>0.39</td>
<td>1.0</td>
<td>17.6</td>
<td>0.43*</td>
</tr>
<tr>
<td>0.49</td>
<td>1.0</td>
<td>25.8</td>
<td>1.4</td>
</tr>
<tr>
<td>31.1 $M_\odot$, 12750 K, Z=0.02</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.28</td>
<td>1.0</td>
<td>22.4</td>
<td>0.96</td>
</tr>
<tr>
<td>0.38</td>
<td>1.0</td>
<td>23.0</td>
<td>0.80</td>
</tr>
</tbody>
</table>

*Mode chosen for hydrodynamic analysis

For initial models, we use 60-zone envelope models discussed by Cox et al. (these proceedings). LBV envelopes are extremely tenuous, with only 0.001% of the stellar mass contained in the outer 95% of the stellar radius. We initiated the models in the most unstable radial mode according to the line analysis (where practicable), with photospheric radial velocity 1 km/sec outward. Table 1 summarizes the model properties, and linear periods and growth rates for the unstable modes. Periods are ~5-40 days, typical of LBV microvariation periods.

3. Hydrodynamics Results

We find for all of the models that one of two results occurs:

a) The pulsation amplitude grows rapidly, but at some point the photospheric radial velocity almost discontinuously becomes very large (outward negative). Thereafter, the velocity of the outer zones may vary as pulsation-induced
Table 2. Nonlinear pulsation results

<table>
<thead>
<tr>
<th>Envelope Y</th>
<th>Optically thick zones with $L_{rad} &gt; L_B$</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>47.28 $M_\odot$, 16950 K, $Z=0.02$</td>
<td>0.38, 17-30, 34</td>
<td>Outburst</td>
</tr>
<tr>
<td>0.48</td>
<td>3, 29-32</td>
<td>Outburst</td>
</tr>
<tr>
<td>0.58</td>
<td>32-33</td>
<td>$V_{max} \sim 100$ km/sec</td>
</tr>
<tr>
<td>54.9 $M_\odot$, 16000 K, $Z=0.01$</td>
<td>0.29, 15-16</td>
<td>Outburst</td>
</tr>
<tr>
<td>0.39</td>
<td>None</td>
<td>$V_{max} \sim 200$ km/sec</td>
</tr>
<tr>
<td>0.49</td>
<td>None</td>
<td>$V_{max} \sim 100$ km/sec</td>
</tr>
<tr>
<td>31.1 $M_\odot$, 12750 K, $Z=0.02$</td>
<td>0.28, None</td>
<td>$V_{max} \sim 90$ km/sec</td>
</tr>
<tr>
<td>0.38</td>
<td>None</td>
<td>$V_{max} \sim 60$ km/sec</td>
</tr>
</tbody>
</table>

Figure 1. Photospheric radial velocity versus time of 47.3 $M_\odot$ model with surface helium abundance 0.48. Outward velocities are negative. The pulsation amplitude begins to grow, but deep zones exceed Eddington limit and the envelope is pushed outward by the radiation.

Figure 2. Photospheric radial velocity versus time of 47.3 $M_\odot$ model with surface helium abundance 0.58. The radial velocity amplitudes rapidly grow from the initial value of $-10^5$ cm/sec, but the lower opacity due to the higher helium abundance limits the pulsation amplitudes. This model settles into semi-regular multimode pulsations.
shocks or waves from inner zones propagate outward, but the photospheric velocity remains negative over several would-be pulsation cycles. It is this phenomenon that we are defining as an outburst (see Fig. 1). Eventually the outer zones decrease in density so much that they are beyond the limits of our equation of state and opacity tables \((\rho < 10^{-12}g \text{ cm}^{-2})\). We cannot as yet predict the amount of mass lost during one of these outbursts because we cannot follow the material as it leaves the surface, nor do we have a means of calculating the expected replenishment of the envelope by material from below the innermost zone into the pulsation driving regions.

b) The photospheric radial velocity of the model grows rapidly, but reaches a limiting amplitude of <200 km/sec, and the model pulsates in one or more modes (see Fig. 2). For this behavior, we may expect pulsation-driven winds, but do not expect an outburst.

Table 2 summarizes the hydrodynamic results. As can be seen, the outbursts can be stabilized with a higher envelope helium abundance, which reduces the opacity and decreases the pulsation amplitude.

4. The Eddington limit and time-dependent convection

An important characteristic that determines whether envelope models will outburst or instead settle into semi-regular pulsations appears to be whether the radiative luminosity of deep zones \((T \geq 100,000 \text{ K})\) exceeds the Eddington luminosity during the pulsation cycle. The Eddington luminosity is defined as

\[
L_E = \frac{4\pi G M c}{\kappa}
\]

Here \(G\) is the gravitational constant, \(c\) is the speed of light, \(\kappa\) is the radiative opacity, and \(M\) is the stellar mass interior to the point of interest. When the opacity increases during a pulsation cycle, convection transports a significant fraction of the luminosity, and so the zone avoids exceeding \(L_E\) (see Fig. 3). In fact, as discussed by Langer (these proceedings), in a static model the convective flux adjusts instantaneously to carry the required luminosity, so the luminosity may never exceed \(L_E\). However, due to the inertia of turbulent eddies, convection takes some time to turn on during each cycle to transport the luminosity predicted by the mixing-length theory, and so the zone will temporarily exceed \(L_E\).

Table 2 lists the model zone numbers where \(L_E\) is exceeded. Only for those models where the deep convective zones repeatedly exceed \(L_E\) do we find an outburst. When the pulsation amplitudes are small, the Eddington luminosity is only exceeded by a few percent. Just before an outburst, \(L_E\) is often exceeded by 20-30%.

5. Conclusions

Our nonlinear pulsation analysis shows that for massive stars near the diagonal high-luminosity part of the Humphreys-Davidson limit,

- Strange mode pulsations grow to large amplitudes, in many cases exceeding 100 km/sec.
Figure 3. Radiative luminosity versus time carried by zone 10 of 31.1 M\(_\odot\) model with surface helium abundance 0.38. The opacity of this zone varies between \(\sim 0.7\) and \(1.1 \text{ cm}^2 \text{g}^{-1}\) during the pulsation cycle. As opacity rises, the temperature gradient steepens and more of the total luminosity is carried by convection.

- When relatively deep regions in the envelope exceed the Eddington luminosity, an outburst occurs. We define an outburst as occurring when the outward photospheric radial velocity suddenly becomes large, and the radii of outer zones monotonically increase during several would-be pulsation periods.

- The Eddington limit is exceeded only when and because convection cannot turn on rapidly to transport the luminosity as the opacity rises during a pulsation cycle. Therefore inclusion of time-dependent convection is critical to our outburst mechanism.

We suggest that massive stars repeatedly outburst and lose mass until their envelopes are enriched in helium and outbursts are stabilized. These stars never evolve past the diagonal part of the H-D limit. For stars of lower initial mass (\(\leq 50 \text{ M}_\odot\)) on their first crossing of the HR diagram, strange mode pulsations occur, but the deep zones never exceed the Eddington luminosity. These stars are able to evolve to become red supergiants. It is possible that after the star loses more mass as a red supergiant, reducing its Eddington limit, it will experience outbursts after blue-looping back into the LBV instability region.

References