TITLE: LINEAR PULSATIONS OF STRANGE MODES IN LBVs

AUTHOR(S): ARTHUR N. COX, JOYCE A. GUZIK, MICHAEL S. SOUKUP

SUBMITTED TO: LUMINOUS BLUE VARIABLES: MASSIVE STARS IN TRANSITION

Kona, Hawaii (October 6 - 11, 1996)

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

MASTER
DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.
DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, make any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.
1. Introduction

Outbursts of the luminous blue variables have been studied for a long time, but a detailed understanding of the mechanism has eluded astronomers. In the last few years it has been recognized that the dramatic increase in outburst brightness is due almost entirely to the luminosity being shifted into the visual band, rather than a true luminosity increase. Some ideas about how these very massive and very luminous stars might display their dramatic increase of visual brightness have been given by many. A sampling is given here.

Maeder (1989) suggested density inversions he noticed in his evolution models might lead to some hydrodynamic effects. Normally the high opacity due to hydrogen and helium ionization in surface layers of stars produces a convection zone that transports a significant fraction of the emergent luminosity. For the very low density blue supergiant envelopes, though, matter cannot carry enough of this luminosity, and the high opacity produces such a high temperature gradient that the density gradient must invert to give the required pressure gradient for hydrostatic balance. We believe that these inverted density gradients lead to pulsation solutions called strange modes, and that these strange modes are very rapidly growing in amplitude.

Appenzeller (1986), Lamers (1986), and Lamers and Fitzpatrick (1988) have proposed that radiation pressure at the Eddington (1921) limit will rapidly expand luminous stars hydrodynamically, and the LBVs are near this limit. This limit, where radiation pressure supplies all the needed pressure gradient to stabilize the star and any additional matter pressure gradient would then expand the star dynamically, depends on the opacity of the surface material. Detailed Eddington limits on the Hertzsprung-Russell (H-R) diagram for various compositions of the envelope matter and total stellar masses have been given recently by Lamers (1995). We suggest that stars approaching this limit will exceed the Eddington limit during the pulsation cycle of strange modes.

The new Livermore OPAL opacities (Rogers and Iglesias(1992) and Iglesias Rogers and Wilson (1992)) seem important for predictions of LBV outbursts. Often an increase of luminosity passing through a stellar layer or an increase of opacity at that point will merely produce convection or increase the fraction of the luminosity it carries. Even a very large luminosity or opacity increase may only make the convection carry all the luminosity without the radiative luminosity exceeding the Eddington limit. As Langer has pointed out at this meeting, the only place where these two increases can make a layer super-Eddington is at the surface where convection can no longer steal some of the emergent radiation. OPAL opacities affect Eddington limit predictions and also give a very
large opacity increase in the deep layers more than 90 percent into the star at a temperature of about 200,000 K. The steep temperature gradient the new opacities produce affects pulsation and convection behaviors to give brief periodic radiative luminosity excesses over the Eddington limit.

An important feature of blue supergiants is that they have so much radiation causing pressure in the envelopes that their equilibrium $\Gamma$, is just over $4/3$. With $\Gamma$ exactly $4/3$ for an entire star, there is neutral equilibrium at any surface radius. The reason is that if the star is expanded somehow, the internal energy of the matter and radiation can supply or absorb all the energy needed to move matter out of or into the gravitational potential well. How low $\Gamma$ affects hydrodynamic motions is discussed by Glatzel and Kiriakidis (in press), but one can expect a low $\Gamma$ envelope would make an outburst easy. Stothers and Chin (1993, 1996) suggest this low gamma mechanism causes LBV outbursts, but they find them too cool on first-crossing tracks in the H-R diagram and at probably too low masses at later evolution stages when they are blue.

Studies of the S Dor LBV by de Koter, Lamers, and Schmutz (1996) show that considerable mass and considerable depth into the envelope is involved in a typical LBV outburst. They find that actually the total luminosity decreases some. This decrease is used to lift the matter out of the gravitational potential well, but it is surely less than one might normally expect due to the low gamma of the envelope. We find in our studies that pulsations do produce explosive motions very deep in our envelope models near 200,000 K.

Langer (1994) suggests that LBV recurrent outbursts cause a great deal of mass loss, and therefore massive blue supergiants never evolve cooler than about 10,000 K. This is entirely reasonable since the Humphreys-Davidson (1979) (H-D) line marking the cool limit of massive stars in the H-R diagram is at that point. Stothers and Chin (1993) get evolution further to the red with the usual mass loss formulas, but they explain the H-D line as being violated only very briefly for the fast evolving red supergiants. Our hydrodynamic calculations show that a lot of mass loss can indeed occur during the many outbursts blueward of the H-D line, and Langer is correct.

The strange modes we consider in this paper have been studied by the Göttingen group under Fricke and Glatzel. See Glatzel (1994). We are interested in strange modes because some are very rapidly growing when conditions are right, and amplitudes reach large radial velocity (200 km/s) and luminosity (0.1 mag). Then the radiative luminosity in deep layers can surpass the Eddington limit during each pulsation cycle, and outbursts occur.

2. Evolution Models

Evolution tracks in the H-R diagram have been calculated to define conditions for models used in both linear and nonlinear calculations. One of these starts on the zero age main sequence with $50 M_\odot$, and the mass loss produces a model with mass $31.1 M_\odot$ at a surface effective temperature of 12,750 K. The homogeneous composition of this starting model is $X=0.70$ and $Z=0.02$. Three other tracks start at $80 M_\odot$, one for $Z=0.02$ and two for $Z=0.01$, and the masses obtained are $47.3$ and $54.9 M_\odot$. Figure 1 shows these tracks that have luminosities near a million $L_\odot$. Also shown is the H-D line.
Figure 1. Evolution tracks for initial 50 and 80 $M_\odot$ models.

These four models are on both sides of the S Dor position, in the center of the observed LBV instability strip. Presumably the LBV phenomenon starts at a blue edge of this instability strip and continues over to the H-D line. Here we have optimized conditions to where most of the LBVs are found.

3. Linear Theory Models

Investigations are first made using linear pulsation theory to map regions of the H-R diagram where radial and nonradial pulsations might occur. The model at 47.3 $M_\odot$, 16980 K (log $T_{\text{eff}}$ = 4.23), and log L=6.10 with a Y composition of 0.38 has a 8.6 day period strange mode with a rapidly growing kinetic energy amplitude of 600 percent per period. Figure 2 displays the temperature structure for the 60 Lagrangian zones of this model. Note the sharp temperature rise near mass layer 16 due to the large opacity increase at 200,000 K. There is strong convection between zone interfaces 16 and 23.

Figure 2. The temperature structure of the 47.3 $M_\odot$ model.

Figure 3 plots the $\Gamma_1$ versus the mass shell number. The exterior mass scale given at the the top of Figures 2 and 3 shows that the gamma down to that steep temperature rise at about a millionth of the mass into the star model is very
near 4/3. This means that there is considerable internal energy in the matter and radiation that can be released to allow an easy outburst.

4. Strange Modes

1. Strange modes appear unexpectedly in the spectrum and are not associated with the usual adiabatic fundamental and overtone modes.

2. These modes appear in high luminosity/mass (low envelope density) models with large nonadiabatic effects.

3. The radius eigenvector is very large at the surface compared to its value at the bottom of the low density envelope.

4. Pulsation driving is by the usual kappa and gamma effects from hydrogen, helium, and iron line opacities and by the "gradient" effect at levels different from normal driving regions.

5. Even though the R CrB and LBV stars show these strange modes with often greatly enhanced surface helium, this envelope composition does not seem necessary to produce them.

The eigensolution for one particular strange mode has pulsation driving all in the layers 40,000 K and exterior, due to the helium ionization kappa and gamma effects, a gradient effect, and the driving disussed by Glatzel (1994) that comes from a density inversion in these layers.

All pulsating variable stars have the possibility of driving from a gradient effect, but often this driving is very small compared to the classical kappa and gamma effects. The mechanism comes from the relatively large motions at the stellar model surface and very small ones deeper. During the compression stage, near surface layers are heated relatively more than the deeper layers, and the temperature gradient is significantly decreased, blocking the flow of luminosity. This acts as a periodic valve just as the kappa and gamma effects do.

A significant density inversion can also block luminosity flow during compression stages, by the fact that sound waves cannot easily move into an increasing density layer. The nonadiabatic reversible approximation (NAR) of Gautschy and Glatzel (1990) shows that the momentum equation alone can
produce a phase change between the pressure and volume variations that create
motion from the internal energy. This pulsation driving is present in our models.

The question about these rapidly growing strange modes has been whether
their large growth rates produce large amplitudes that could lead to outbursts.
The amplitude does increase rapidly as expected, but after only a few pulsational
cycles it limits to something similar to the observed LBV microvariations.

5. The Cause of LBV Outbursts

1. Evolution and considerable mass loss produce radial and nonradial pulsa-
tions in normal and strange modes where the LBV stars are found.

2. These stars very near their Eddington luminosity limit at many levels in
their envelope exceed this limit for deep layers during the pulsation cycle.

3. The outburst is triggered when the rapidly growing pulsation amplitude
repeatedly brings the opacity and luminosity to the Eddington limit.

4. The outbursts require pulsations for their trigger, and they occur only for
effective surface temperatures near the Humphreys-Davidson line.

5. The outburst episodes end when the lower opacities of the higher exposed
envelope helium is established. Then only pulsations occur in the instabil-
ity strip between about 10,000 and 30,000 kelvin.

References

Appenzeller, I. 1986, Luminous Stars and Associations in Galaxies, IAU Sym-
posium 116, eds. C. de Loore and A. J. Willis, p. 139


Lamers, H. J. G. L. M. 1986, Luminous Stars and Associations in Galaxies, IAU
Symposium 116, eds. C. de Loore and A. J. Willis, p. 157

Lamers, H. J. G. L. M. 1995, Astrophysical Applications of Stellar Pulsations,
eds. R. S Stobie and P. A. Whitelock IAU Colloq 155, p. 176


Maeder, A. 1989, Physics of Luminous Blue Variables, Kluwer, p.15


5