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# Pulsations and Outbursts of Luminous Blue Variables

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**Abstract.**

We propose an outburst mechanism for the most luminous stars in our and other galaxies. These million solar luminosity stars, with masses (after earlier mass loss) of between 20 and maybe 70 solar masses, are pulsationally unstable for both radial and low-degree nonradial modes. Some of these modes are "strange," meaning mostly that the pulsations are concentrated near the stellar surface and have very rapid growth rates in linear theory. The pulsation driving is by both the high iron line opacity (near 150,000 K) and the helium opacity (near 30,000 K) kappa effects. Periods range from 5 to 40 days. Depending on the composition, pulsations periodically produce luminosities above the Eddington limit for deep layers. The radiative luminosity creates an outward push that readily eases the very low gamma envelope to very large outburst radii. A key point is that a super-Eddington luminosity cannot be taken up by the sluggish convection rapidly enough to prevent an outward acceleration of much of the envelope. As the helium abundance in the envelope stellar material increases by ordinary wind mass loss and the luminous blue variable outbursts, the opacity in the deep pulsation driving layers decreases. This makes the current Eddington luminosity even higher so that pulsations can then no longer give radiative luminosities exceeding the limit. For the lower mass and luminosity luminous blue variables there is considerably less iron line opacity driving, and pulsations are almost all caused by the helium ionization $\kappa$ effect.

## 1. Introduction

Pulsating stars have been known for over 400 years, and our understanding that they do actually pulsate has been known now for over 80 years since the Shapley (1914) analysis. These stars start pulsating when they evolve to conditions where their thermodynamic properties allow small internal perturbation motions to grow. But most of these stars evolve on to more stable conditions with hardly any long lasting effects on their structure or evolution. The luminous blue variable (LBV) stars, however, are so greatly affected by pulsations and consequent mass loss that their subsequent fate is enormously changed.

This report follows earlier ones where we discuss linear theory pulsations in LBV models (Cox et al. 1995, 1997) and a nonlinear study of LBVs and possible outbursts (Guzik et al. 1997). Many details of the stellar models used in this paper are described in these earlier presentations.

## 2. Massive Star Evolution Calculations

Initial main sequence masses of 50 and 80 $M_\odot$ with Z=0.02 are followed with the Iben (1963,1965,1975) evolution code including extensive mass loss. This mass loss can be due to the usual hot wind or rotation as discussed by Langer (1997). Our model masses after evolution to the LBV region are 31 and 47 $M_\odot$. Many levels in the models are close to the Eddington luminosity limit where the radiation pressure gradient established by the radiation diffusion flow through the model can completely support the matter against gravity. However, Langer (1997) shows that a model cannot actually exceed this Eddington limit, because convection can carry an almost unlimited luminosity and always keep the radiative luminosity sub-Eddington. Further a super-Eddington model cannot even be constructed, because it will not be able to conform to the prescribed hydrostatic equilibrium with a non-zero mass.

The 31 $M_\odot$ model lies below the horizontal part of the Humphreys-Davidson line in the Hertzsprung-Russell diagram. Even though it is located among other stars that are LBVs, and some layers in the model are near the Eddington limit, hydrodynamic calculations show that we cannot make this model display outbursts. Presumably the LBVs (such as the low Z SMC star R40) seen at this luminosity have masses even lower than 31 $M_\odot$ after they have evolved to the red and lost considerable mass as red supergiants. Then they have returned to higher effective temperatures (like 12,000 K) with a mass near 20 $M_\odot$.

Both our 47 and 31 $M_\odot$ evolution models have significant helium enhancement at the surface over the primordial value, because the extensive mass loss exposes material that has had hydrogen burned away. For this study various compositions from Y=0.28 to 0.58 are used, even though, strictly, additional evolution models should be constructed. We assume further that convection and pulsations homogenize the entire envelope composition down to as much as $10^{-3}$ of the stellar mass at about $10^6$ K and at less than 0.1 of the photosphere radius of near $10^{13}$ cm. Evolution models show only a slight helium composition gradient in the extended outer envelope anyway.

## 3. The Cause of Outbursts

Here are some features of the outbursts that we have found from linear and nonlinear (see also Despain, Guzik, and Cox 1998) calculations of stellar models with parameters near the actual observed LBVs:

1. Evolution and considerable mass loss produces models that display radial and nonradial pulsations in normal and "strange" modes.
2. During pulsations these stars periodically exceed the Eddington luminosity limit and should at least give enhanced mass loss.

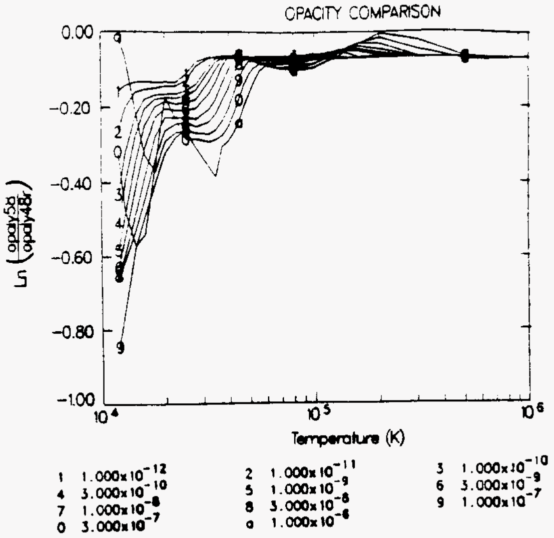

Figure 1. The natural logarithm of the ratio of the Y=0.58 to Y=0.48 opacity for temperatures and densities ($gm/cm^3$) in massive star models.

3. An outburst is triggered when the rapidly growing pulsation amplitude repeatedly brings the opacity and luminosity to exceed the Eddington limit at deep levels.
4. Outburst episodes end when the lower opacities of the higher exposed envelope helium is established. Then only pulsations occur in an instability strip between about 10,000 and 30,000 kelvin.

This Eddington luminosity limit is given by the well-known formula:

$$L_{Edd} = 4\pi GMc/\kappa$$

with $M$ the total stellar mass that creates the gravity and $\kappa$ the local opacity. This limit is almost reached in the static models in the convecting iron line opacity layers around 150,000 K and the helium ionization layers near 30,000 K.

Figure 1 shows the ratio of the opacity for Y=0.58 and 0.48 of a Z=0.02 (galactic) stellar composition. This demonstrates the somewhat odd phenomenon that higher helium in the mixture gives a lower opacity over the entire range of temperature and density in a massive star envelope model.

The high opacities in the envelopes can sometimes create density inversions, and they cause "strange" pulsation modes. Disturbances can amplify as they traverse decreasing density surface layers of pulsating stars, but they can get weaker if they enter layers where the density increases with radius. This can isolate regions of a pulsating star and put the pulsation displacements mostly very near the surface. The displacements must, however, be large enough in the super-Eddington layers so that the radiation flow actually exceeds the limit each pulsation cycle.

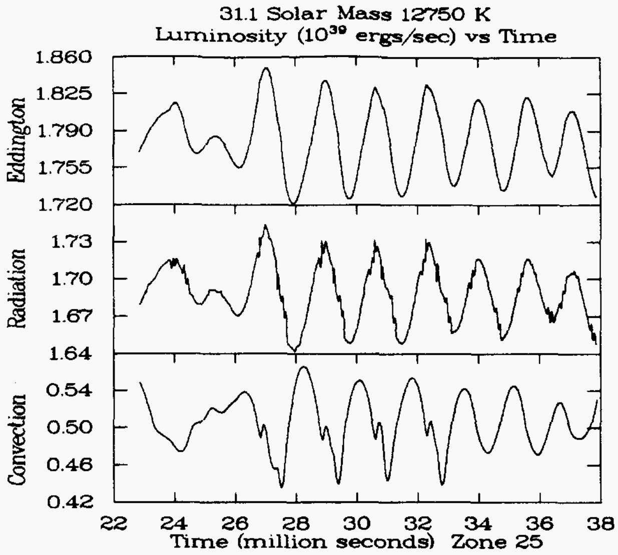

Figure 2. The upper panel gives the time history for the Eddington luminosity limit, the middle panel, the radiation luminosity, and the bottom panel, the convection luminosity for a 31 $M_\odot$ hydrodynamic model. There is a small lag between the radiation minimum and the convection maximum.

## 4. Time-Dependent Convection

A key point in the hydrodynamics of the massive star outbursts is that convection cannot be counted on to carry unlimited luminosity as it can do in static models. We use a simplified time-dependent convection formulation discussed by Cox and Giuli (1968) that uses the standard mixing length theory and a lagging, which reflects the relative time scale of the convective eddies and the pulsations.

Figure 2 show the time history of the Eddington luminosity limit, the radiation luminosity, and the convective luminosity for a 31 $M_\odot$ model that definitely does not outburst. Similar plots for an outbursting model are more difficult to interpret, but one is explained in the accompanying paper by Despain, Guzik, and Cox (1998). We note that the Eddington and radiation luminosities almost exactly track together, since the opacity is the only varying quantity for the Eddington luminosity and the main variable for the radiation flow. The radiation luminosity never exceeds the Eddington limit, and only a multimode pulsation occurs.

The interesting behavior of the convection comes about mostly because its luminosity flow reaches a maximum when zones are at their maximum density. That time, however is usually the time of the opacity maximum and the radiation flow minimum. As time moves on and the density decreases with the layer expansion, the convection carries less, not more, luminosity. It cannot take the luminosity flowing through the layers from radiation and protect the radiation luminosity from increasing toward the Eddington limit. The star nevertheless protects itself from an outburst, because the Eddington limit increases in step with the radiation.

For outbursting models, the same phenomenon occurs, but the radiation does periodically exceed the Eddington limit to give a persistent outward push of the exterior envelope. In any case, the convection actually aids an outburst rather than preventing it for cases with higher luminosity or lower stellar mass.

## 5. Conclusions

1. Models in the known stellar mass range can undergo pulsations and hydrodynamic outbursts as observed for LBVs.
2. Observed LBV luminosities and effective surface temperatures are in the predicted pulsation instability strip for many pulsation modes including "strange" modes.
3. Both radial and nonradial modes are driven by the $\kappa$ effect of the deep iron line opacity and the high surface helium exposed by earlier extensive mass loss.
4. After many outbursts and the accompanying mass loss, the surface helium abundance is so large that only pulsations and no outbursts can occur.
5. The role of luminosity transported by time-dependent convection that is included in the hydrodynamic calculations is very important because of its phasing relative to the radiation luminosity.

## References

Cox, A. N., Guzik, J. A., Soukup M. S., & Morgan, S. M. 1995, in Astrophysical Applications of Stellar Pulsation, ASP conference Series, Vol 83, R. S. Stobie & P. A. Whitelock, 192

Cox, A. N., Guzik, J. A., & Soukup M. S. 1997, in Luminous Blue Variables: Massive Stars in Transition, ASP Conference Series, Vol 120, A. Nota & H. J. G. L. M. Lamers, 133

Cox, J. P. & Giuli, R. T. 1968, in Principles of Stellar Structure, New York: Gordon and Breach, 1044

Despain, K. M., Guzik, J. A., & Cox, A. N. 1998, these proceedings

Guzik, J. A., Cox, A. N., Despain, K. M., & Soukup M. S. 1997, in Luminous Blue Variables: Massive Stars in Transition, ASP Conference Series, Vol 120, A. Nota & H. J. G. L. M. Lamers, 138

Iben, I. Jr. 1963. ApJ, 138, 452

Iben, I. Jr. 1965, ApJ, 141, 993

Iben, I. Jr. 1975, ApJ, 196, 525

Langer, N. 1983, in Luminous Blue Variables: Massive Stars in Transition, ASP Conference Series, Vol 120, ed. A. Nota and H. J. G. L. M. Lamers, 83

Shapley, H. 1914, ApJ, 40, 448

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