Luminous Blue Variable Outbursts from the Variations of Helium Opacity

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Luminous blue variables are evolved massive stars that exhibit poorly understood variability on timescales from months to years with significant mass loss rates[1–5]. They typically reach an effective temperature of $\approx 9000\mathrm{K}$ during outbursts[3,6]. These variations and large mass loss rates are believed to be caused by the radiation force on the cooler, more opaque outer layers that can balance or even exceed the force of gravity, although the exact mechanisms for the outburst and variability are unknown and cannot be calculated in one dimension[7]. Here we report three dimensional simulations of radiation-dominated massive stars, which show that helium opacity plays an important role for the outburst and setting the observed effective temperature $\approx 9000\mathrm{K}$. It also likely triggers the episodic mass loss at rates of 10^{-7} –

$10^{-5} M_\odot/yr$. **The helium opacity peak only shows up in our three dimensional simulations but not in one dimensional calculations because the envelope structures need to be determined self-consistently with convection. The simulations not only reproduce similar observed long time scale variabilities, but also predict that convection causes irregular envelope oscillations and 10-30% brightness variations on a typical timescale of a few days, and reaches larger amplitudes for even cooler stars. These short time scale variabilities should be observed with future high cadence observations.**

We used 60 million CPU hours on the supercomputer Mira awarded by Argonne Leadership Computing Facility for the INCITE program, as well as computational resources from NASA and NERSC, to solve the three dimensional (3D) radiation hydrodynamic equations[8] and follow the physically realistic evolution of these envelopes (see the Method section for the simulation setup). These simulations take the fixed core mass and luminosity coming from the bottom boundary as input and then determine the envelope structure, effective temperature and mass loss rate self-consistently. We performed three simulations: a model corresponding to a $M_{\rm i} = 80 M_\odot$ star with $\log(L/L_\odot) = 6.2$ and $T_{\rm eff} = 9000$K (`T9L6.2`), one for the same initial mass with $\log(L/L_\odot) = 6.4$ and $T_{\rm eff} = 19000$K (`T19L6.4`) and one $M_{\rm i} = 35 M_\odot$ star with $\log(L/L_\odot) = 6.0$ and $T_{\rm eff} = 19000$K (`T19L6`). Although the three runs are based on one dimensional (1D) models for stars with different initial masses and/or at different evolutionary stages, they share similar properties such as density and the Eddington ratio (the ratio of radiation to gravitational acceleration), at the iron opacity peak. The main difference in these models is the pressure scale height at the iron opacity peak, which results in different total mass and optical depth above the convective region and hence different surface temperatures[9].

Locations of the three models in the Hertzsprung-Russell diagram as well as 1D stellar evolution tracks are shown in Figure 1. The histories of spherically averaged radial profiles of density, turbulent velocity, radiation temperature and opacity for the run `T9L6.2` are shown in Figure 2. The envelope is convectively unstable at the iron opacity peak [7,9,10], where density increases with radius around that region in the initial hydrostatic structure. Convection takes about 10 dynamical times (≈ 43 hours) to destroy the density inversion, which causes high density clumps to rise, expand and cool to a temperature below $\approx 6 \times 10^4$K. Since the density of these cooled clumps is much higher compared with the density at that temperature prior to the onset of convection, a strong helium opacity peak appears (bottom panel of Figure 2). The local radiation acceleration is now 10 times larger than the gravitational acceleration, which causes a large fraction of the envelope to expand dramatically, with most of the gas above that region blown away. Mass flux of gas which is unbound (positive total energy[11]) leaving our simulation domain can reach an instantaneous rate $\approx 0.05 M_{\odot}/$yr. After 400 hours, the envelope settles down to a steady-state structure, as shown in the right panels of Figure 2. Convection is still operating around $80 - 90 R_{\odot}$, with a second helium opacity peak around $200 R_{\odot}$. Convection also causes envelope oscillations with a typical time scale of a day. The time averaged location of the photosphere, where the total Rosseland optical depth to the outer boundary of the simulation box is 1, is at $342.8 R_{\odot}$ as indicated by the dashed blue lines in Figure 2 with an averaged radiation temperature 9.06×10^3K at that location. The mass-averaged turbulent velocity is only 1% of the sound speed deep in the envelope, but it becomes supersonic near the photosphere, causing strong shocks and large temperature and density fluctuations near the photosphere. During each oscillation cycle, as indicated by both the density and turbulent velocity in the right panel of Figure 2, part of the mass becomes unbound with mass loss rate $\approx 5 \times 10^{-6} M_\odot/\mathrm{yr}$. This simulation naturally produces a massive star with luminosity, effective temperature and mass loss consistent with LBVs during an outburst. The traditional 1D models cannot capture these properties because of two physical processes that can only occur in the 3D simulations. There are supersonic turbulent motions that provide effective turbulent pressure support to maintain the extended envelope, and radiative and convective energy transport through the turbulent opacity peak regions. In addition, conversion from radiation to kinetic energy is not well captured by the traditional mixing length theory in 1D models [9].

The run `T19L6.4` shows a similar evolution history and turbulent structures with one snapshot shown in Figure 3. Due to a smaller pressure scale height and a smaller optical depth across the typical convective element, the gas rising due to convection experiences a much smaller temperature change. This causes a much lower value of the opacity at the helium peak compared with the run `T9L6.2`, and thus a smaller total optical depth above the iron opacity peak region. Although the luminosity for this run is a little bit larger than the previous model, the less significant helium opacity peak places the time averaged location of the photosphere at a smaller radius $102R_\odot$ with a higher effective temperature $1.87 \times 10^4\mathrm{K}$, which confirms that without the helium opacity peak, the star will not undergo an outburst and move to the constant temperature strip. The presence of a smaller helium opacity peak results in a substantial reduction of the envelope oscillation amplitude and a lower associated mass loss rate of $\approx 1 \times 10^{-6} M_\odot/\mathrm{yr}$.

The final run T19L6 has very similar properties to T19L6.4, in particular a comparable value of the pressure scale height at the iron opacity peak. However, the model is calculated for a smaller core mass and a smaller luminosity. In steady state the envelope solution has a $T_{\rm eff} = 1.89 \times 10^4$K with time averaged photosphere radius of $63.7 R_\odot$, and an episodic mass loss rate associated with envelope oscillations of only $\approx 5 \times 10^{-7} M_\odot$/yr. This confirms that when the iron opacity peak is found in a region with a small pressure scale height, the effective temperature remains too hot for the helium opacity to become significant, and the massive star model stays closer to the S Dor instability strip.

Our simulations predict that LBVs in outburst should show irregular variability with typical timescales of days. In particular, we expect the variability pattern to be different for massive stars on the S Dor instability strips and during outburst, as shown in Figure 4. For massive stars with effective temperature near 9×10^3K, a significant helium opacity peak exists in the envelope and causes large amplitude oscillations. The predicted stellar brightness then varies by a factor of $\approx 1.5-2$ in a day during the steady state as shown in the top panel of Figure 4. For stars with hotter effective temperatures near 1.9×10^4K and a weaker helium opacity peak, the variability during the steady state has a much smaller amplitude. However, the luminosity can still vary by $\approx 20\%$ on timescales of a week to a few weeks, corresponding to the thermal time scale of the envelope above the iron opacity peak. This kind of variability has been seen in recent high cadence observations of massive stars [12–14], and the correlation between variability and effective temperature can be tested with future observations. The envelope is loosely-bound and dominated by turbulent convection (Figure 2), so the oscillation at the stellar surface is chaotic. However, there are moments in the envelope evolution when the majority of the photosphere is falling back onto the core, as suggested by the integrated luminosity shown in Figure 4. This can potentially explain the time dependent behavior of P-Cygni and inverse P-Cygni profiles found in some LBVs[13,15].

The mass loss rates we obtain from our steady-state simulations are broadly consistent with the inferred mass loss rate during both the quiescent and outburst phases of LBVs [5,13]. We find that the physical mechanism responsible for driving the mass loss in LBV stars is the interaction of their large radiative flux with opacity peaks that appear in the optically thick envelope of these stars as they expand and cool. Importantly, while the iron opacity peak is strongly metallicity dependent, as long as a turbulent stellar envelope cools to low-enough temperatures, the helium and hydrogen opacity peaks will always cause large Eddington factors. This suggests that this mode of mass loss may be less sensitive to metallicity than line-driven winds[16]. Traditionally, mass loss due to radiation force on the ultraviolet lines in the optically thin region is thought to be the dominant mechanism for winds in these massive stars[17,18], although other models are likely important for outbursts[3,19]. Our work suggests that it is important to study these mechanisms with the turbulent envelope as found by our simulations.

The simulations also suggest possible paths for the transition between the S Dor instability strip and the outburst phase as indicated by the dotted black lines for the observed LBVs in Figure 1. When stars expand due to nuclear evolution and a significant helium opacity peak appears, the star will undergo the first outburst. The amount of mass initially above the iron opacity peak region can only sustain the mass loss rate for ~ 10 years, while the thermal time scale below the convective region in the envelope is also comparable to ~ 10 years. The star may lose a significant fraction of the mass above the iron opacity peak via the wind before it has time to adjust to a new structure to keep this large mass loss rate. This will reduce the total optical depth above the iron opacity peak and increase the effective temperature. When the helium opacity peak is significantly reduced, these stars will return to the S Dor instability strip. As the iron opacity peak moves to the deeper region of the envelope on the thermal timescale, this process can repeat. Alternatively, if the massive star is in a binary system as suggested for some LBVs [20] and the companion deposits mass on the surface of the star, the additional mass will likely be ejected by the massive star as we found in our initial evolutions for each numerical simulation. This can be a trigger of the giant eruption of some LBVs. Detailed properties of this process will need to be studied with future calculations.

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Figure 1: Hertzsprung-Russell diagram for luminous blue variables (LBVs, solid black dots). Shaded areas represent the locations where LBVs are most commonly found[5,6]: the diagonal band is the S Dor instability strip (LBVs in quiescence), while the vertical shaded band is the LBVs in outburst. Dotted lines show observed excursions from quiescence to outburst. The solid red, green and blue lines correspond to main sequence, 1D stellar evolution tracks with different initial masses as calculated by different groups [22–24]. The locations of our three simulated stars are indicated by colored polygons. The dashed black line is the Humphreys-Davidson (HD) limit[1].

Figure 2: History of the spherically averaged radial profiles for the run `T9L6.2`. The left and right panels break at $t = 426$ hours to separate the initial transition and the steady state structures. From top to bottom, the four panels are for density ρ ($\rho_0 = 3.6 \times 10^{-9}$ g/cm^3), turbulent flow velocity v scaled with the local isothermal sound speed (c_g, 1.05×10^6 cm/s at the photosphere), radiation temperature T_r ($T_0 = 1.67 \times 10^5$K) and opacity κ ($\kappa_0 = 0.34$ cm^2/g). The dashed blue lines indicate the location where the time averaged optical depth to the outer boundary of the simulation domain is unity during the steady state.

Figure 3: A snapshot of 3D density (left half panel) and radiation energy density (right half panel) for the run `T19L6.4`. The radial range in this plot covers $14.8R_\odot$ at the bottom to the photosphere at $102R_\odot$. Convection develops at the bottom due to the iron opacity peak at $44.6R_\odot$. The photosphere shows large scale plumes, which also cause strong variations of the radiation temperature at the photosphere across the surface of the star. A video showing the evolution of this simulation is available online.

Figure 4: History of the total luminosity measured from the outer boundary of the simulation box for the three simulations `T9L6.2` (top, $M_{\rm i} = 80M_\odot$), `T19L6.4` (middle, $M_{\rm i} = 80M_\odot$) and `T19L6` (bottom, $M_{\rm i} = 35M_\odot$). The vertical dashed red lines indicate the time at which the density inversion in the initial conditions has been removed due to convection. The effective temperature and averaged luminosity during the steady state for the three simulations are labeled in each panel.

Methods

Typical LBVs have luminosities 6×10^5 to $\sim 4 \times 10^6$ times the solar luminosity, and effective temperatures either hotter than $\sim 2 \times 10^4$K in quiescence or around 9000K during outburst as shown in Figure 1. We use the 1D stellar evolution code `MESA`[7,25–27] to evolve solar metallicity stars with initial mass $M_{\rm i}$ = 35 and $80M_\odot$ to this region of the Hertzsprung-Russell (HR) diagram[9]. Although these 1D evolution models for stars in this regime are very uncertain as illustrated in Figure 1, they do provide a useful first approximation of the physical conditions in the radiation dominated envelopes of these stars.

One important feature of these regions is the presence of the iron opacity peak at temperatures $T \simeq 1.8 \times 10^5$ K due to lines of iron-group elements. The opacity there is often a factor of a few larger than that from free electron scattering and can cause the local radiation acceleration to exceed that from gravity[7]. In this situation, the envelope is unstable to convection at the location of the iron opacity peak[7,28], with the properties of convection and envelope structure depending crucially on just how deep within the star this iron opacity peak occurs[9]. The opacity can, in principle, increase further to values 100 times that of electron scattering when the temperature drops below $1 - 4 \times 10^4$K. This arises from helium and hydrogen recombination, but only when the density exceeds $\sim 10^{-9}$ g/cm^3, a value much larger than what is realized in 1D hydrostatic structures around this temperature range.

We take the typical luminosity, density and gravity at the location of the iron opacity peak in our 1D models and construct envelopes in hydrostatic and thermal equilibrium in spherical polar geometry as the initial conditions for our 3D simulations. The whole simulation box initially covers temperature range from 10^4 to 10^6K. The bottom boundary has a density and temperature order of magnitudes larger than the values at the iron opacity peak and remains relatively still. Both OPAL Rosseland and Planck mean opacity tables[29] are included in the simulations to capture the momentum and thermal coupling between the radiation field and gas[10]. The outer boundary of the simulation box is at least three times the photosphere radius for all the simulations.

Data Availability The simulation data is available from the corresponding author on request.

Code Availability The code we used to do the simulations, Athena++ with the radiative transfer module, is available from the corresponding author on request.