LBVs – Variabilities and the Formation of Nebulae

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Let us start simple:
What defines a Luminous Blue Variable?
Defining a Luminous Blue Variable

I shall refer to the non W-R or "other," hot stars as "luminous blue variables," or LBV, in my talk.

Conti 1984

... this is a quite broad definition but at least excluded

- classical main-sequence O stars
- Wolf-Rayet stars

...and restricted that sample to more evolved objects that

→ need to be **luminous** ↔ massive
→ need to be **blue** ↔ hot
→ need to be **variable**

at that time already three classes were known to fulfill these criteria

**Hubble Sandage Variables**
**P Cygni typ stars**
**S Doradus Variables**
LBVs – a grand unification of

Hubble-Sandage Variables

P Cyg type star

S Dor Variables

(M 33) (Burggraf 2005)

(Weis 2003)

(Hubble & Sandage 1953)

(Weis 1999)

(van Genderen 1997)
Defining a Luminous Blue Variable

I shall refer to the non W-R or "other," hot stars as "luminous blue variables," or LBV, in my talk.

Conti 1984

\[
\text{LBV} = \text{Hubble-Sandage Variables} + \text{P Cygni-typ stars} + \text{S Dor Variables}
\]
Defining a Luminous Blue Variable

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Conti 1984

LBV = Hubble-Sandage Variables + P Cygni-typ stars + S Dor Variables

...13 years later ...
Defining a Luminous Blue Variable

I shall refer to the non W-R or "other," hot stars as "luminous blue variables," or LBV, in my talk.

Conti 1984

The terminology has stuck and it is now appropriate, given the occasion of this very energetic Workshop, to ask whether or not revisions or a redefinition might be in order. First of all, I think most of us would agree that the term “variable” really means, within the context of the LBV phenomena, an “outburst” (but I do not propose changing LBV to LBO, especially since the latter already has significance within the financial field). It also appears clear that outbursts are either “major” or “minor”. The former has occurred to only three stars so far as the historical record is concerned: η Car, P Cyg and SN 1961v.

Conti 1997
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The terminology has stuck and it is now appropriate, given the occasion of this very energetic Workshop, to ask whether or not revisions or a redefinition might be in order. First of all, I think most of us would agree that the term “variable” really means, within the context of the LBV phenomena, an “outburst” (but I do not propose changing LBV to LBO, especially since the latter already has significance within the financial field). It also appears clear that outbursts are either “major” or “minor”. The former has occurred to only three stars so far as the historical record is concerned: η Car, P Cyg and SN 1961v.
Defining a Luminous Blue Variable by Variability

Photometric Variability

“minor outburst”

● minor fractions of magnitudes, on timescales of days and weeks

● fractions to a few magnitudes, on timescales of several years

“major outburst”

many magnitudes, more or less instantly
Defining a Luminous Blue Variable by Variability

Photometric Variability

“minor outburst”

● minor fractions of magnitudes, on timescales of days and weeks

many magnitudes, more or less instantly

“major outburst”

micro-variations

seen in LBVs and many other massive stars

LBV with a giant eruption

→ stars unstable, in the HRD close to de Jager-/Humphreys-Davidson-/Eddington- / \( \Omega \Gamma \) -limit*

→ LBV in eruption

S Dor Cyclus

→ stars changes \( T_{\text{eff}} \) and Radius

→ SN imposter

* pick whatever is you favorite ☺
Defining a Luminous Blue Variable by Variability

- minor outburst (Conti 1997)
- small scale variation
- micro-variations
- LBV in eruption ↔ S Dor cycle
Microvariations of Luminous Blue Variables

- typical amplitudes are 0.1-0.5 mag
- typical timescales few days to several weeks

Fig. 2. Detailed light and colour curves of the ~ 40 d microvariations in the hump of the descending branch of HR Car’s normal SD phase (with a maximum at JD 2446250). Note that the magnitude scales for the colour curves are twice that for the light curve

(example of micro-variations in the lightcurve of the LBV HR Carinae)

(van Genderen et al. 1997)
Defining a LBV – minor outburst ↔ S Dor cycle

photometric variability

S Dor Cycle

(Stahl et al. 2001)
Defining a LBV – minor outburst ↔ S Dor cycle

spectral variability

S Dor Cycle

(Stahl et al. 2001)
Defining a LBV – minor outburst $\leftrightarrow$ S Dor cycle

S Dor cycle $\rightarrow$ variabilities are coupled

$T_{\text{eff}}$ changes $\leftrightarrow$ spectrum changes $\leftrightarrow$ flux in filter band changes

(Stahl et al. 2001)
Defining a LBV – minor outburst ↔ S Dor cycle

- Log $L/L_\odot$
- Log $T_{\text{eff}}$
- $M_{\text{bol}}$

- Humphreys Davidson Limit
- AG Car
- SN 1987A
- Main Sequence
- LBVs
- LBV Eruptions

- Red Supergiants

- 120 $M_\odot$
- 85 $M_\odot$
- 60 $M_\odot$
- 40 $M_\odot$

- 6.5
- 6.0
- 5.5
- 5.0
Defining a LBV – minor outburst ↔ S Dor cycle

- $M_{bol}$ vs. $\log T_{eff}$
- Humphreys Davidson Limit
- AG Car
- SN 1987A
- Cool Hypergiants
- LBVs
- LBV Eruptions

Red Super Giants

- $L/L_\odot$ vs. $\log T_{eff}$
Defining a LBV – minor outburst ↔ S Dor cycle
Classification of various S Dor subtypes

I. By the stars activity

**strong-active (s-a)**
light amplitues > 0.5 mag
e.g.: AG Car, HR Car, HD 160529, WRA 751, R127, S Dor, R71, R110, R143...

**weak-active (w-a)**
light amplitues < 0.5 mag
e.g.: η Car, P Cyg, HD 168607, CygOB2#12, R99, R123, R74, R81, R149...

**ex- and dormant (ex/dormant)**
no variations detected in the 21\textsuperscript{st} century (given the data present)

**candidate**
divided into
positive (+)
negative (-)
non-candidates (0)

![Graphs showing light amplitudes for different classes of S Dor subtypes](image-url)
Classification of various S Dor subtypes

II. By timescale

**short-S Dor (S-SD)**
S Dor cycle shorter as 10 yr

**long-S Dor (L-SD)**
S Dor cycle longer as 20 yr

it also exists a

**very-long-term-S Dor (VLT-SD)**
S Dor cycle 20-50 yrs
→ now in L-SD

see poster by Burggraf et al. on Var C in M33

Is the S Dor cycle and its timescales different for different metallicities?

Maybe!
see talk/poster Bomans et al. on transients at very low Z
Security advise !

Don't leave your LBV unattended !
Security advise!
Don't leave your LBV unattended!
Security advise!
Don't leave your LBV unattended!

(Humphreys et al. 1999)

Weis et al. 2001

giant eruption

(a) Eta Car

(Weis et al. 2001)
Defining a Luminous Blue Variable by Variability

**major outburst**

↕

LBV giant eruption

↕

\( \eta \) Car variables

↕

SN imposters

(Conti 1997)
Defining a Luminous Blue Variable by Variability

η Carinae

η Car variables

SN 1961V

SN 1954J

P Cygni

major outburst (Conti 1997)

LBV giant eruption

SN imposters

(Humphreys 1999)
Warning !!!
What looks like giant eruption may not always be one!

The case of SN 2002kg

SN2002kg is was detected in NGC2403
“The object was at mag 19 +/- 0.3, and possibly showed a brightening trend, from 2002 Oct. 26 to 2003 Jan. 1.”
Schwartz et al. ,IAUCircular No. 8051
Defining a Luminous Blue Variable by Variability
The case of SN 2002kg!

SN 2002kg
= the brightening of the LBV V37 in NGC 2403

Tamman & Sandage (1968) first identified V37 as a blue irregular variable star ↔ fitting to LBV

SN 2002kg is found to agree with the position of V 37 by Weis & Bomans (2005) and Van Dyk (2005)

SN 1954J giant eruption
yes ✅

SN 2002kg giant eruption
no ❌
The LBV eruption of V37 ↔ SN2002kg

Lightcurve of V37 with the SN 2002kg detection → the star brightend but it was neither a giant eruption nor a classical S Dor cycle.

H$_\alpha$ image of the area and V37 taken before the SN 2002kg. Here V37 is found in bright H$_\alpha$ emission. → strong emission line star → indications for a nebula

(Weis & Bomans 2005)
The LBV eruption of V37 ↔ SN2002kg

SN 2002kg ↔ V37

Hα image of the area and V37 taken before the SN 2002kg. Here V37 is found in bright Hα emission.

→ strong emission line star
→ indications for a nebula

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Is V37 a giant eruption imposter?

(Weis & Bomans 2005)
The LBV eruption of V37 ↔ SN2002kg

Lightcurve of V37 with the SN 2002kg detection → the star brightened but it was neither a giant eruption nor a classical S Dor cycle.

Is V37 a giant eruption imposter?
...No not again a new acronym...

Hα image of the area and V37 taken before the SN 2002kg. Here V37 is found in bright Hα emission.
→ strong emission line star
→ indications for a nebula

(Weis & Bomans 2005)
LBVs – The nebula basics

Variable stellare winds and giant eruptions
→ ideal conditions to create **circumstellar nebulae**

- strong N lines ↔ CNO processed material
Morphology of LBV nebulae

Morphology

- several are quite spherical (e.g. S 61)
- a few do show outflows or convexity (e.g. Sk -69° 279)
- rarely irregular (best example R 143)

Morphology of LBV nebulae

Morphology

- a quite large number are **bipolar**
  → either like **hourglass** shaped nebulae (e.g. η Car, HR Car)
  → or as bipolar attachments → **caps** (e.g. WRA 751, R 127)

(Weis et al. 1997 & Weis 2003)
Multi-shell nebulae – several phases?

P Cygni (MW)

S 61 (LMC)

“outer shell”

“inner shell”

S 61

P Cygni
Sizes of LBV nebulae

Sizes

- the **smallest** are the Homunculus and HD168625 both $\sim 0.2$ pc
- the **largest** is Sk -69° 279 with $\sim 4.5$ pc or 6.2 pc (with Fil N)
- the **majority** has a size between 1-2 pc
- the **LMC nebulae** are larger compared to the **Galactic**

(Weis 2009, Weis & Duschl 2002)
LBV nebulae – on scale!
Kinematics of LBV nebulae

Expansion velocities

- the slowest is Sk -69°279 with 14 km/s
- the fastest is η Carinae with up to at least $\geq 3200$ km/s
- the average is around 50 km/s
- LMC LBVs have in general a slower expansion velocity

Outflows

- some have outflows that move faster (e.g. S 119)

Bipolarity

- is detected kinematically
  - either as two expansion ellipses (e.g. AG Car)
  - or the bipolar expansion of the attached caps (e.g. WRA 751)
## LBV nebulae in numbers

<table>
<thead>
<tr>
<th>LBV</th>
<th>host galaxy</th>
<th>maximum size</th>
<th>radius</th>
<th>(v_{\text{exp}})</th>
<th>kinematic age</th>
<th>morphology</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\eta) Carinae</td>
<td>Milky Way</td>
<td>0.2/0.67</td>
<td>0.05/0.335</td>
<td>300*/10 – 3200</td>
<td></td>
<td>bipolar</td>
</tr>
<tr>
<td>AG Carinae</td>
<td>Milky Way</td>
<td>1.4 × 2</td>
<td>0.4</td>
<td>~ 25*</td>
<td>~ 30</td>
<td>bipolar</td>
</tr>
<tr>
<td>HD 168625</td>
<td>Milky Way</td>
<td>0.13 × 0.17</td>
<td>0.075</td>
<td>30</td>
<td>1.8</td>
<td>bipolar ?</td>
</tr>
<tr>
<td>He 3-519</td>
<td>Milky Way</td>
<td>2.1</td>
<td>1.05</td>
<td>61</td>
<td>16.8</td>
<td>spherical/elliptical</td>
</tr>
<tr>
<td>HR Carinae</td>
<td>Milky Way</td>
<td>0.65 × 1.3</td>
<td>0.325</td>
<td>75*</td>
<td>4.2</td>
<td>bipolar</td>
</tr>
<tr>
<td>P Cygni</td>
<td>Milky Way</td>
<td>0.2/0.84</td>
<td>0.1/0.42</td>
<td>110 – 140/185</td>
<td>0.7/2.1</td>
<td>spherical</td>
</tr>
<tr>
<td>Pistol Star</td>
<td>Milky Way</td>
<td>0.8 × 1.2</td>
<td>0.5</td>
<td>60</td>
<td>8.2</td>
<td>spherical</td>
</tr>
<tr>
<td>Sher 25</td>
<td>Milky Way</td>
<td>0.4 × 1</td>
<td>0.2 × 0.5</td>
<td>30 – 70</td>
<td>6.5 – 6.9</td>
<td>bipolar</td>
</tr>
<tr>
<td>WRA 751</td>
<td>Milky Way</td>
<td>0.5</td>
<td>0.25</td>
<td>26</td>
<td>9.4</td>
<td>bipolar</td>
</tr>
<tr>
<td>R 71</td>
<td>LMC</td>
<td>&lt; 0.1?</td>
<td>&lt; 0.05?</td>
<td>20</td>
<td>2.5?</td>
<td>?</td>
</tr>
<tr>
<td>R 84</td>
<td>LMC</td>
<td>&lt; 0.3 ?</td>
<td>&lt; 0.15?</td>
<td>24 (split)</td>
<td>6 ?</td>
<td>?</td>
</tr>
<tr>
<td>R 127</td>
<td>LMC</td>
<td>1.3</td>
<td>0.77</td>
<td>32</td>
<td>23.5</td>
<td>bipolar</td>
</tr>
<tr>
<td>R 143</td>
<td>LMC</td>
<td>1.2</td>
<td>0.6</td>
<td>24 (split)</td>
<td>49</td>
<td>irregular</td>
</tr>
<tr>
<td>S Dor</td>
<td>LMC</td>
<td>&lt; 0.25?</td>
<td>&lt; 0.13?</td>
<td>&lt; 40 (FWHM)</td>
<td>3.2 ?</td>
<td>?</td>
</tr>
<tr>
<td>S 61</td>
<td>LMC</td>
<td>0.82</td>
<td>0.41</td>
<td>27</td>
<td>15</td>
<td>spherical</td>
</tr>
<tr>
<td>S 119</td>
<td>LMC</td>
<td>1.8</td>
<td>0.9</td>
<td>26</td>
<td>33.9</td>
<td>spherical/outflow</td>
</tr>
<tr>
<td>Sk –69° 279</td>
<td>LMC</td>
<td>4.5 × 6.2</td>
<td>2.25</td>
<td>14</td>
<td>157</td>
<td>spherical/outflow</td>
</tr>
</tbody>
</table>

* expansion velocity per lobe

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JUST OUT  
Weis 2012 in *Eta Car and the Supernova Impostors*  
A&A library  
(eds. Davidson & Humphreys)
The case of bipolarity

About 50% of the all LBV nebulae show signs of bipolarity! Taking only the galactic LBVs the fraction is about 70%.

Hints for stellar rotation? Hints for a metallicity effect?

The cause of bipolarity → Rotation?

HR Car

AG Car

(Weis et al. 1997)

(Weis 2009)
The cause of bipolarity $\rightarrow$ Rotation?

HR Car

AG Car

$v \sin i = 150$ km/s

$v \sin i = 85-190$ km/s

both are fast rotating stars!

velocities from Groh et al. 2006, 2009
What we know and learn from LBV nebulae

LBV nebulae facts

- morphologies are *spherical*, *elliptical* to *irregular*
- a *large fraction* (50-75%) shows *bipolarity*
- LMC nebulae are generally *larger* as those in the *Milky Way*
- expansion velocities range typically between 10-150 km/s with the exception of η Carinae (≥ 3200 km/s)
- LMC nebulae are generally *slower* as those in the *Milky Way*
- some LBV nebulae show *multiple shells*
What we know and learn from LBV nebulae

- **bipolar** nebulae (see → AG Car & HR Car)
  - → result of the **faster rotation** of the central stars

- **lower** metallicity LBVs (LMC) have **larger, slower** expanding and **fewer bipolar nebulae**
  - → **metallicity depend mass loss and ejecta mechanism**
  - → **coupling of metallicity and faster rotation**

- **multiple shell structures** in the nebulae
  - → various wind ← S Dor phases
  - → **multiple eruptions**
So back to the start, what do we know defines a Luminous Blue Variable?
LBVs – The observational background

- photometric and spectroscopic variable
- S Dor variability is a photometric ↔ spectroscopic ↔ T
- may undergo a giant eruption
- variability in general irregular!
- close to Humphreys-Davidson limit
The LBVs in the HRD – the theory side

![Graph showing the Hertzsprung-Russell diagram with LBVs and LBV eruptions marked.](image)
The LBVs in the HRD – the theory side

Geneva Modells
Z=0.02
V_{rot} = 300 km/s
The LBVs in the HRD – the theory side

- evolved massive star
- comparison with rotation models $\rightarrow M_{\text{ini}}$ as low as $22 M_\odot$
- high mass loss $\sim 10^{-6}...-3 M_\odot \text{yr}^{-1}$
- LBV phase short $\sim 2 \times 10^4 \text{yrs} \rightarrow$ is it?
- close to Eddington or if rotating $\Omega \Gamma$-limit
There is no unique LBV feature → therefore no unique classification scheme!

Giant eruptions
Irregular photometric variations
Proximity to instability limit

a fitting $\log L_\odot$ and $\log T_{\text{eff}}$
S Dor cycle
Nebula
Spectral variations
There is no unique LBV feature → therefore no unique classification scheme!

Proximity to instability limit

irregular photometric variations

S Dor cycle

giant eruptions

spectral variations

...?

nebula

a fitting log $L_\odot$ and log $T_{\text{eff}}$

How many do we have to check with yes ✔️ to classify it as LBV?
There is no unique LBV feature → therefore no unique classification scheme!

How many do we have to check with yes ✓ to classify it as LBV?

To be or not to be a LBV. That is the question.