Active OB stars: structure, evolution, mass loss, and critical limits
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Eruptive outflow phases of massive stars

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Abstract. I review recent progress on understanding eruptions of unstable massive stars, with particular attention to the diversity of observed behavior in extragalatic optical transient sources that are generally associated with giant eruptions of luminous blue variables (LBVs). These eruptions are thought to represent key mass loss episodes in the lives of massive stars. I discuss the possibility of dormant LBVs and implications for the duration of the greater LBV phase and its role in stellar evolution. These eruptive variables show a wide range of peak luminosity, decay time, expansion speeds, and progenitor luminosity, and in some cases they have been observed to suffer multiple eruptions. This broadens our view of massive star eruptions compared to prototypical sources like Eta Carinae, and provides important clues for the nature of the outbursts. I will also review and discuss some implications about the possible physical mechanisms involved, although the cause of the eruptions is not yet understood.

Keywords. instabilities, circumstellar matter, stars: evolution, stars: mass loss, supernovae: general, stars: winds, outflows

1. Introduction and Background

Almost sixty years have passed since, as a result of attempts to produce standard candles for cosmology, Hubble & Sandage (1953) discovered the class of luminous, blue, irregular variables in M31 and M33 that we now collectively refer to as luminous blue variables (LBVs) in any galaxy. A few key conferences in the late 1980s and 1990s established some paradigms for LBVs and the evolution of massive stars in general, some of which may be in need of revision.

In the context of this conference on "active" OB stars, the LBVs are perhaps a hideous extreme example of stellar activity. However, they can be viewed as cases where the effects of rotation, pulsation, binaries, and perhaps even magnetic fields may have rather extreme consequences when the a star is near the Eddington limit. In that sense, there is hopefully some synergy between LBVs and the various other types of stars discussed at this meeting.

LBVs exhibit so-called "microvariability" in their photometry and also undergo well-known S-Doradus excursions when the star changes color at relatively constant bolometric luminosity (although see the talk by J. Groh in these proceedings). However, they are most notable and mysterious for their giant eruptions, when the stars are thought to increase their bolometric luminosity to be above the classical Eddington limit, during which time they may eject large amounts of mass — anywhere form 0.1 – 10 $M_\odot$. Smith & Owocki (2006) have argued that when this is combined with the facts that LBV eruptions repeat, and that mass-loss rates for O-type stars are lower than we used to think, that LBVs probably dominate the shedding of the H envelope in massive single stars. This may have significant implications, since LBV eruptions do not necessarily depend on metallicity.

However, we still have no clear idea what causes the giant eruptions of LBVs, and we have no good formulation for how the eruptive behavior scales with initial mass and metallicity, or if it depends on binarity. Since the dominant mass-loss machanism in stellar evolution is so poorly understood, we cannot have very much faith in the predictions of the fates of massive stars in stellar evolution models, or how this scales with metallicity.

We do, however, know that giant LBV eruptions certainly occur because we observe them, and advances can be made in constraining their properties. Giant LBV eruptions are bright and can be seen in other galaxies. They are detected by accident in systematic supernova searches that are conducted — like Hubble & Sandage's early work — in the pursuit of standard candles for cosmology, and so they are sometimes called "SN impostors". Several dozen SN impostor giant eruptions have now been seen in nearby galaxies, but LSST will vastly increase the number of these transients. Hopefully this will allow us to improve our knowledge of the statistics of LBVs. For now, we must be content with studying the few examples we have and gleaning as many clues about their physics as we can. In this paper, I briefly review some of the observed properties of LBV stars, and I emphasize some new results including the distribution of observed properties in giant LBV eruptions and their connection to Type IIn supernovae. Much of what I discussed in my talk at IAU Symposium 272 is presented in more detail in two recent papers (Smith *et al.* 2010a; Smith & Frew 2010), and the reader is reffered to these for more information.

2. Lifetime of the LBV Phase, and Ducks that Don't Quack

> "If it looks like a duck, and quacks like a duck, we have at least to consider the possibility that we have a small aquatic bird of the family anatidae on our hands."
> ...Douglas Adams

This is a slightly different formulation of the more familiar "If it looks like a duck..." phrase, which was often used in connection with LBV eruptions in the 1980s and 1990s (e.g., Conti 1995, 1997; Bohannan 1997), suggesting that you can't really be sure that a duck is a duck unless you hear it quack. The point was that although pretty much everything in the upper left part of the HR diagram is luminous, blue, and at least somewhat variable if you look closely enough, the classification "LBV" was to be reserved for a specific class of stars that are observed to undergo more violent eruptions (i.e. they "quack" rather loudly), and that this therefore indicated some particular inherent instability in the star, which is not present in all supergiants. In the same breath, however, it was sometimes admitted that a star which had erupted in the past (or will erupt in the near future) might not necessarily be exhibiting signs of that instability *right now.* This problem is illustrated in Figure 1.

LBVs are extremely rare — there are only a handful known in the Milky Way or in any nearby galaxy. However, there is a larger number of stars that closely resemble LBVs in their observed spectral properties and location on the HR diagram. Some of these have massive circumstellar shells that resemble LBV shells, as in several recent examples detected by Spitzer (Gvaramdze *et al.* 2010; Wachter *et al.* 2010). These are typically called "LBV candidates" until they are actually seen to have an eruption. The Ofpe/WN9 stars are a good example of a class of stars which resemble LBVs and often have circumstellar shells; there are documented examples of confirmed LBVs that are Ofpe/WN9 stars in their quiescent hot states (e.g., R127, AG Car). If Ofpe/WN9 stars are really dormant LBVs, it would imply that LBVs may go through relatively long periods of time when they are not erupting. In other words, they may have extended "dormant" phases in between major eruptions, like volcanoes or geysers.

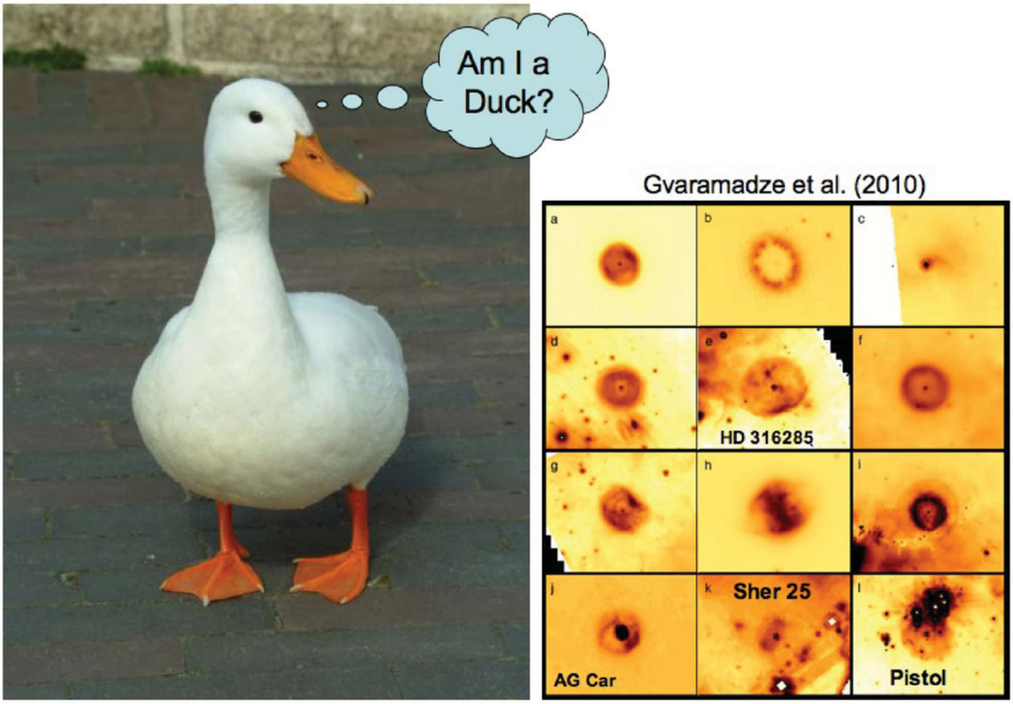

Figure 1. The reader can deduce that the object on the left is obviously a Duck, even though this conference proceedings volume is not accompanied by an audio CD containing a recording of it quacking. On a related note, the panel at right shows several hot massive stars surrounded by LBV-like dust shells detected in the mid-IR (Gvaramadze *et al.* 2010).

Another sign of long dormant phases of LBVs is illustrated by the example of P Cygni, which is the nearest and the first LBV. It underwent a giant LBV eruption in 1600 AD, with a second eruption 55 years later. After being faint for another 50 years, it brightened at the beginning of the 18th century. Since then, however, *P Cygni hasn't done much of anything to suggest that it is an unstable star*. Had we started observing it around 1700 AD, instead of 1600 AD, we would never know that it is an LBV. We would see a relatively tame blue supergiant with a strong wind and a shell nebula, and we would simply call it an LBV candidate. (Note that P Cygni is not as hot as an Ofpe/WN9 star, suggesting that there may be many other blue supergiants that are dormant LBVs as well.) Similarly, many stars discovered in the Galactic center resemble LBVs in their luminosity and spectral properties, but because they are only seen in the IR, we do not have the benfit of many decades or centuries of continuous photometric monitoring, so we have not necessarily observed eruptive behavior in all the Galactic center LBVs.

The rarity of LBV has led to important conjectures about their evolutionary phase and the lifetime of the LBV phase itself. Many authors have discussed this, but the argument usually goes something like this, as discussed in the review by Bohannan (1997): There were 5 LBVs and 115 WR stars known in the LMC at that time. If we assume that all WR stars are descended from LBVs, and that the WR lifetime is the core-He burning lifetime of about $5{\times}10^5$ yr, the rarity of LBVs then suggests that the LBV phase only lasts only a few 10^4 yr. It was widely concluded, therefore, that the LBV phase represents an extremely brief and fleeting *transitional* phase between the core-H burning main sequence of O-type stars and the core-He burning phase of WR stars.

This line of reasoning suffers from some fallacies, and the derived age is probably wrong. It ignores the possibility of dormant phases of LBVs, as noted above, and offers no good explanation for the large number of LBV candidates and other blue supergiants that are necessarily evolved massive stars as well. It also ignores the fact that about 1/3 of stars counted as "WR stars" are actually WNH stars (see Smith & Conti 2008) and are probably not in core-He burning yet.

Returning to the analogy with volcanoes, one could reproduce a similar fallacy: there are typically something like 1 or 2 major volcanic eruptions on Earth each year (where "major" means more than 0.1 km^3 of tephra). Some of us experienced the unfortunate consequences of this for international travel earlier this year. One could then say that since there are several thousand major mountains on Earth, each of which has an average geological age of around 10^8 yr, that the lifetime of a typical volcano is only a few 10^4 yr. This is, of course, a severe underestimate for the lifetime of a volcano because volcanoes spend most of their time in dormant phases. We know this because mountains with a crater or with evidence for a history of eruptions are counted as real volcanoes, and may erupt again in the future. Similarly, one could take inventory of the number of ducks quaking at any instant and vastly underestimate the true number of aquatic birds of the family anatidae.

Deriving the correct lifetime for LBVs depends on the "duty cycle" of the unstable LBV phase. In other words, we need to know what fraction of the time an LBV might be dormant by our observational standards, and correct for that. We have no theoretical prediction of this time, since there is no theoretical prediction of LBVs. There is, however, an expectation that LBVs recover from major eruptions and go through a relatively quiescent period where they re-establish thermal equilibrium. Both P Cygni and η Car have mulitple shell nebulae that suggest time periods of order 10^3 yr in between major eruptions. Moreover, Massey *et al.* (2007) counted only 6 LBVs in M31 and M33, but they counted over 100 LBV candidates. This suggests a factor of 10-20 more LBVs than are counted by active LBVs at any time, implying a duty cycle of 5–10% for the manifestation of LBV instability during the greater evolutionary phase in which we find LBVs. If we re-do the calculation above (now including the fact that 1/3 of WR stars are WNH), then we find that the lifetime over which a massive star could be an LBV is more like $(2\text{–}5)\times10^5$ yr.

This paints a very different picture for the evolutionary state of LBVs, where they spend a substantial fraction (or all) of their core-He burning lifetime as an LBV (or candidate LBV), punctuated by intermittent episodes of eruptive instability. If some of these LBVs make it all the way to core collapse before shedding their H envelopes, it may explain the observed connection between LBVs and Type IIn supernovae (Smith *et al.* 2007, 2008, 2010a, 2010c; Gal-Yam & Leonard 2009; etc.).

Of course, the comments above are predicated on the notion that all WR stars are descended from LBVs, allowing us to calculate the LBV lifetime by comparison to the assumed WR lifetime. This hypothesis may be wrong if, for example, a substantial fraction of WR stars have shed their H envelopes via Roche lobe overflow in binary systems (see, e.g., Smith *et al.* 2010c for implications from Type Ibc supernovae). In that case, the fraction of LBVs+candidates to WR stars depends on both the relative lifetimes and the fraction of massive stars in close binaries. One gets the impression that our paradigms of massive star evolution need to be taken back to the drawing board.

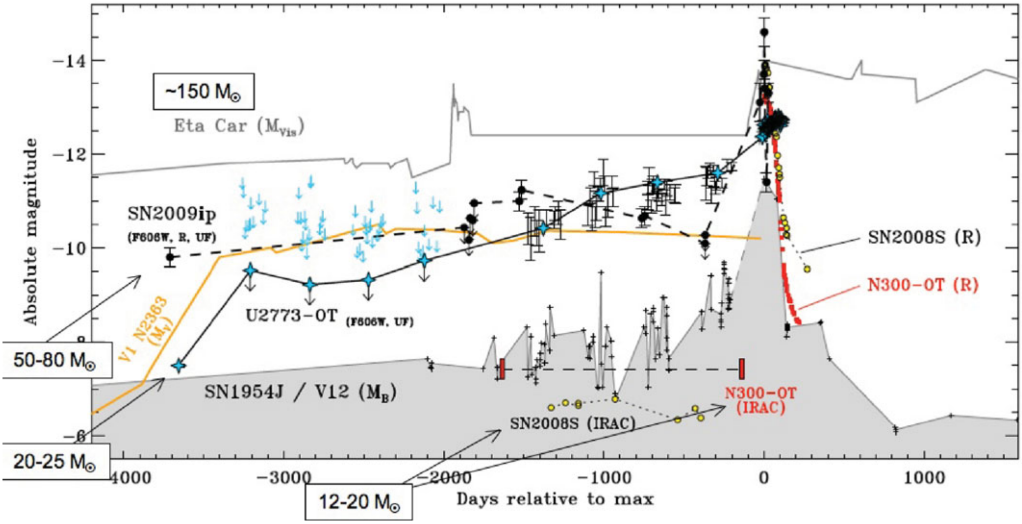

Figure 2. Light curves of various LBV-like transients (from Smith *et al.* 2010a), with a few cases where approximate initial masses for the progenitor stars have been estimated. References for individual sources of photometry can be found in that paper.

3. A Diverse Range of Observed Properties

LBVs are by definition associated with the most luminous and most massive stars in any galaxy, but their initial mass range is actually rather wide. LBVs are thought to arise from stars with initial masses ranging from 20 or 25 M$_\odot$ up to the most massive stars known (Smith, Vink & de Koter 2004). (The lower-luminosity LBVs with initial masses of 20 or 25 $M_\odot$ up to about 40 $_\odot$ are thought to reach their unstable state only after they have been through substantial mass loss in a previous RSG phase, thereby increasing their L/M ratio.) This mass range is perhaps a result of how we identify them: we define the LBV variability as a brightening at visual wavelengths that corresponds roughly to the star's bolometric correction (e.g., Humphreys & Davidson 1994). The S Doradus instability strip is slanted on the HR diagram, so that more luminous LBVs are hotter in their quiescent state. As a result, these hotter and more luminous LBVs have a larger bolometric correction, and consequently, brighten more at visual wavelengths when they undergo an S Dor eruption.† These are the classical LBVs. LBVs at the bottom end of the initial mass range have cooler quiescent temperatures and, consequently, smaller bolometric correction and less pronounced brightenings in a normal S Dor stage. In fact, if we were to extrapolate the S Dor instability strip to lower luminosities and cooler temperatures, it would cross the temperture for cool 7000–8000 K eruptive states of LBVs at luminosities that correspond to initial masses of $\sim$20 $M_\odot$. In other words, whatever instability causes the LBV phase might manifest itself somewhat differently below 20–25 $M_\odot$, and we might not recognize these stars as LBVs because of how we define the observed LBV variability.

In fact, recent studies of extragalactic transient sources have revealed some transients that closely resemble LBV giant eruptions, but which — unexpectedly — seem to have progenitor stars of lower masses around 10–20 $M_\odot$ or even lower. These transients and other LBVs are reviewed recently by Smith *et al.* (2010a; see also Smith *et al.* 2009,

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† Note that it was originally hoped that calibrating this would allow LBVs to be used as standard candles.

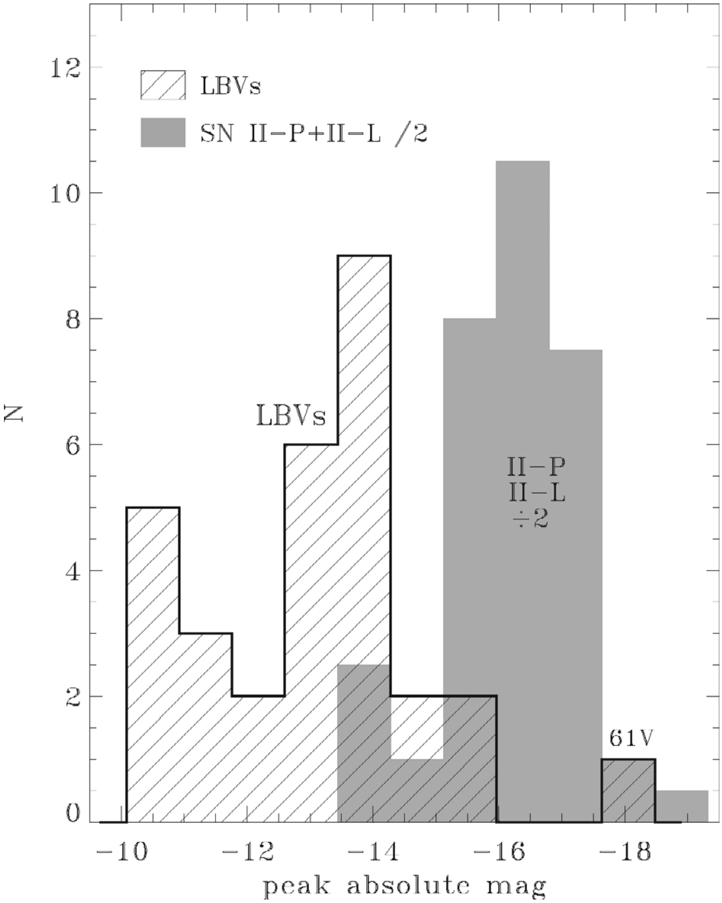

Figure 3. A histogram of the distribution of peak absolute magnitudes for LBV-like eruptions (hatched) compared to normal Type II-P and II-L supernovae (gray; numbers divided by 2) from the Berkeley SN search (figure from Smith *et al.* 2010a; see that paper for details). The LBV farthest to the right is SN 1961V, which Smith *et al.* (2010a) have argued is not really an LBV, but rather, a true core-collapse SN IIn.

2010b; Prieto *et al.* 2008, 2009; Thompson *et al.* 2009; Gogarten *et al.* 2009). The true nature of these sources is still debated, however; it is not clear if they are manifestations of LBV-like instability extending to stars with lower-initial masses, or if they are something altogether different originating from intermediate-mass stars. The light curves for some LBV-like transients are shown in Fig. 2 (from Smith *et al.* 2010b), concentrating on some sources that show detections of their progenitor stars before a giant LBV-like eruption. This is meant to demonstrate the range of initial luminosities and masses for stars that undergo giant LBV-like eruptions. Some of the stars even show precursor variability before the eruption begins, like SN 2009ip and UGC2773-OT (Smith *et al.* 2010b).

Smith *et al.* (2010a) has also discussed the diversity in the observed properties of the eruptions themselves. Figures 3 and 4 show histograms of the distributions of peak absolute visual magnitude (a combination of V and R magnitudes) and the distribution of expansion speeds (measured from Hα). LBV-like eruptions span a range in absolute peak magnitude from around –10 to –16 mag, peaking at –14 mag. The luminous end of the distribution overlaps with the faintest core-collapse SNe, but one can usually distinguish the two based on spectra (see Smith *et al.* 2009, 2010b). The low-luminosity end of the

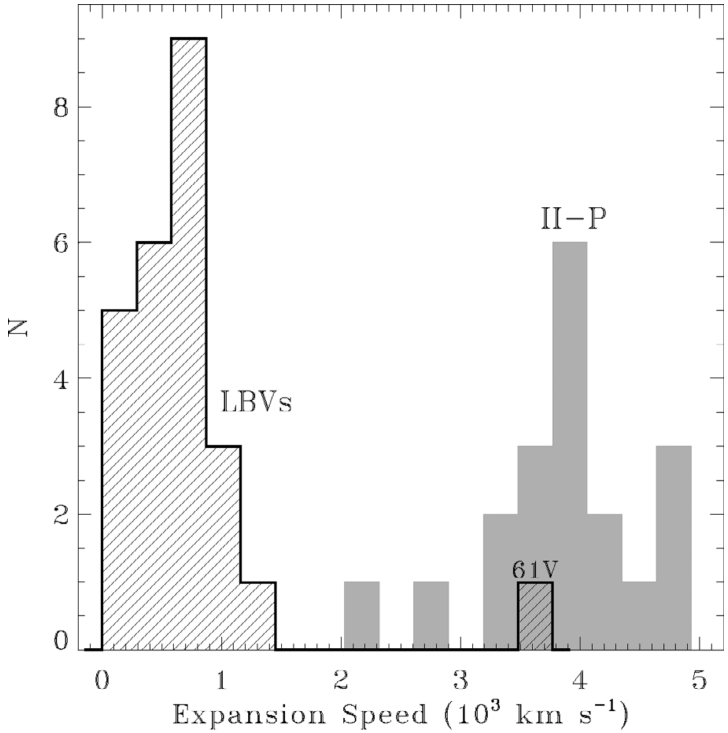

Figure 4. A histogram of the expansion speeds for LBV-like eruptions (hatched) compared to SNe II-P (figure from Smith *et al.* 2010a; see that paper for details).

distribution of LBV-like eruptions is muddy; there may be a mix of LBV giant eruptions and S Doradus outbursts (see Smith *et al.* 2010a for more details). One problematic case is the prototypical SN impostor SN 1961V, which is much brighter than any other LBV eruption. SN 1961V also stands out in its observed expansion speed (Fig. 4) which is much faster than other LBVs and more in line with core-collapse SNe. Based on these points and other information, Smith *et al.* (2010a) have argued that SN 1961V was in fact not an LBV giant eruption, but a true core-collapse SN IIn. The other LBVs have expansion speeds that range from around 100 to 1000 km s^{-1}, much slower than speeds for core-collapse SNe, indicating less energetic explosions.

4. Some Detailed Examples

There has been a recent increase in studies of extragalactic transients that seem analogous to LBV giant eruptions, perhaps due in part to the increased community-wide interest in transient sources of all types, and perhaps also because a substantial fraction of the SN community seems to finally be getting bored of Type Ia SN cosmology. Whatever the reason, extragalacitc LBV-like eruptions are receiving more attention and we have more examples of them, with the result that the increased number do not support some long-help paradigms about LBVs.

In particular, LBV eruptions were thought to always have cool ∼8000 K pseudo photospheres (Humphreys & Davidson 1994), but this is apparently wrong. Some do indeed exhibit apparent temperatures in this range and have F-supergiant like spectra; the recent transient UGC2773-OT is a good example, and its spectrum is shown in Fig. 5. However, several LBV giant eruptions exhibit hotter temperatures with smooth blue continua and

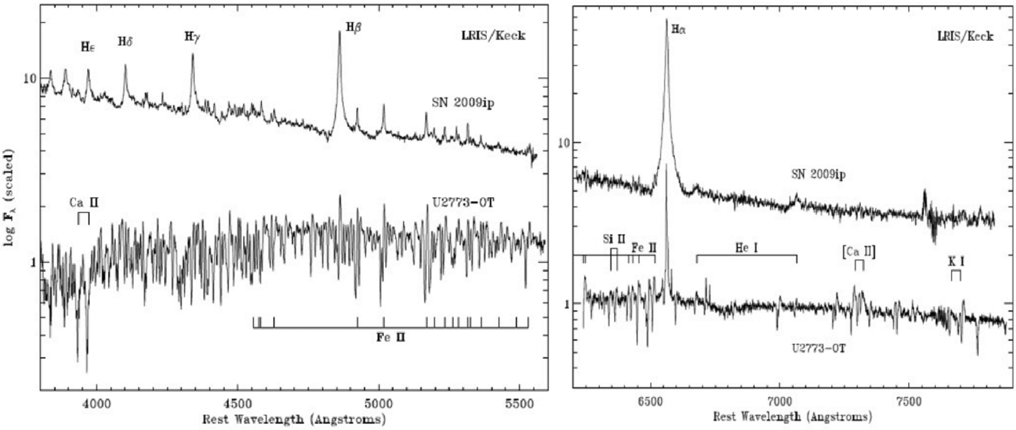

Figure 5. Visual-wavelength spectra of two recent transients, demonstrating the range of spectral properties in LBV outbursts. SN 2009ip is an example of a hotter LBV, with blue continuum and strong and relatively broad Balmer emission lines, plus evidence for a blast wave. UGC 2773-OT is more characteristic of cooler LBV wind-dominated spectra in their F supergiant state. Both are from Smith *et al.* (2010b).

strong Balmer emission lines. Some even show evidence for fast blast waves of 5,000 km s^{-1} out in front of the bulk of ejecta moving at around 600 km s^{-1}. SN 2009ip is an example of this (Figure 5; Smith *et al.* 2010b), as is the more familiar case of η Carinae (Smith 2008). The spectral diversity of these LBV giant eruptions is discussed in more detail by Smith *et al.* (2010a).

An exciting recent development is that some LBVs exhibit multiple brief eruptions, partly as a consequence of continued monitoring. It was already known that both η Car and P Cygni had secondary eruptions about 50 yr after their initial giant eruptions (Humphreys & Davidson 1994; Humphreys *et al.* 1999). However, a recent study by Smith & Frew (2010) shows an even more complicated situation for η Car, with two brief precursor eruptions in 1838 and 1843 that preceded the peak of the Great Eruption in 1844, and which appear to have occurred near times of periastron. Moreover, the LBV-like eruption SN 2000ch (see Wagner *et al.* 2004) was later discovered to have multiple subsequent eruptions in 2008 and 2009 (Pastorello *et al.* 2010). Very recently, Drake *et al.* (2010) reported the discovery of another subsequent eruption of SN 2009ip, which was discussed above. In all cases, the repeated eruptions appear to be very brief (few to 10^2 days), and not the multi-year affairs as seen in more conventional LBV eruptions. The physical cause of these repeated brief outbursts is not yet known, but Smith *et al.* (2010a) and Pastorello *et al.* 2010) have mentioned the possibility of binary interactions, among other potential causes. Smith (2010) discusses a particular way that such a model might work.

Lastly, there is continually mounting evidence that LBV-like eruptions seem to precede the particular class of supernovae known as Type IIn, where the narrow (n) lines of H arise when the SN blast wave encounters extremely dense circumstellar material ejected immediately before the outburst. This has been discussed elsewhere by multiple authors at previous conferences. The point I would like to emphasize here is that the range of properties inferred for the precursor eruptions of SNe IIn seems to roughly match the diversity in properties exhibited by LBV eruptions themselves (expansion speed, mass-loss rates, composition), but there are no other known stars with sufficient mass-loss rates to match SN IIn progenitors. The SN IIn/LBV connection will likely become clearer with

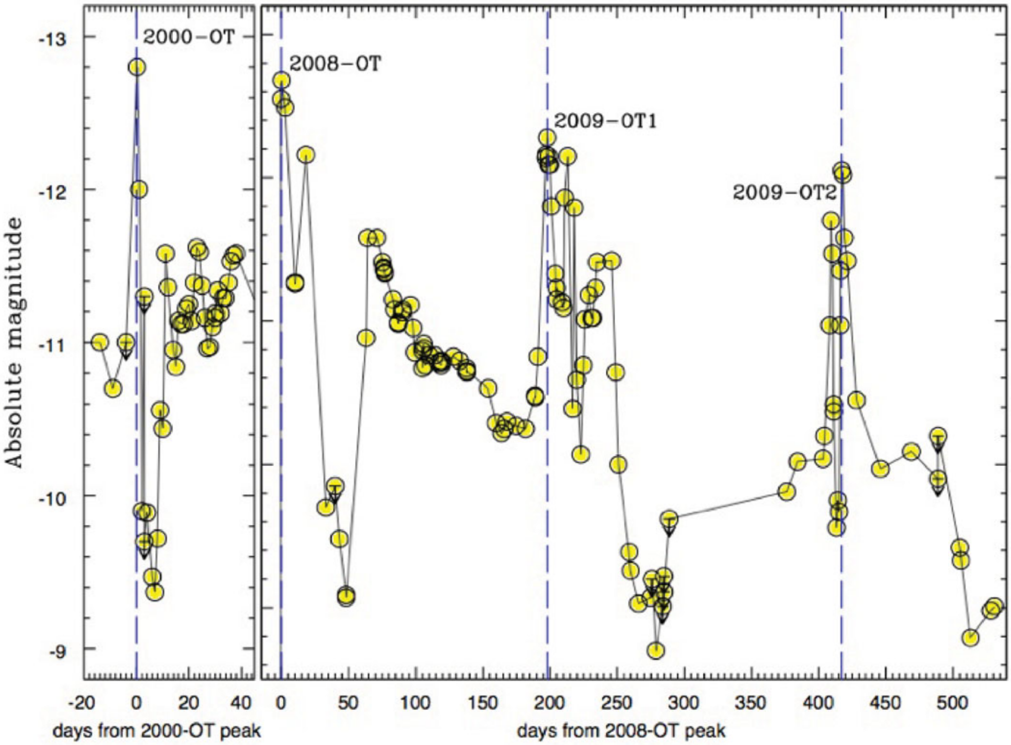

Figure 6. The R-band light curve of the multiple eruptions of SN 2000ch (in 2000, and then again in 2008-2009), from Pastorello *et al.* (2010).

more studies of LBV eruptions and of SNe IIn, and especially cases where LBV progenitor stars are seen to explode as SNe IIn (e.g., Gal-Yam & Leonard 2009).

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