

# Giant eruptions of very massive stars

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**Abstract.** Giant eruptions or supernova-impostor events are far more mysterious than true supernovae. An extreme example can release as much radiative energy as a SN, ejecting several  $M_{\odot}$  of material. These events involve continuous radiation-driven outflows rather than blast waves. They constitute one of the main unsolved problems in stellar astrophysics, but have received little theoretical attention. The most notorious giant-eruption survivor,  $\eta$  Carinae, is amazingly close to us for such a rare event. It offers a wealth of observational clues, many of them quite unexpected in terms of simple theory.

## 1. Introduction

Let me steal a metaphor from Tom Wolfe. Some of us think that a Demon lives near the Eddington Limit. If you (as a massive star) try to approach that limit, he intervenes before you get very close to it. He shakes you so violently that you lose mass and energy, and he hurls you back away from the edge. After watching this happen to a number of stars, we have never seen the Demon's face. In hindsight his behavior almost makes sense in terms of physics, and it dramatically alters the evolution of very massive stars. But the only certain factor is that no theorist predicted it.

This idea grew from several disparate topics. Three decades ago, Luminous Blue Variable stars (LBVs) attracted attention because their sporadic mass-loss events could explain why there are no yellow and red supergiants with  $L > 10^6 L_{\odot}$  [1]. LBVs have  $L/M > 0.4 (L/M)_{\text{Edd}}$ . After 1980 the nature of  $\eta$  Carinae's giant eruption in 1830–1860 also became apparent; as usual, one really good example provided better clues than dozens of less extreme ones. That event expelled 10 to 30  $M_{\odot}$  of material and the same amount of light as a typical supernova, in a timescale roughly 50 times as long as a SN event, and the star survived. By 1990 the role of eruptive mass loss in the most massive stars was widely recognized [2]. But then a sort of collective amnesia occurred after 1995; astronomers almost seemed to forget the earlier work. When mass loss in ordinary hot-star winds was reassessed downward around 2005, invalidating the published evolutionary tracks [3], experts again proposed eruptive loss. In fact its role had been familiar to many people 15 years earlier (see many refs. in [2]).

Meanwhile, SN surveys revealed abnormal explosions in other galaxies. Instead of obvious blast waves, they produced slower, more continuous outflows resembling  $\eta$  Car's great eruption [4]. Some were labeled "Type IIn supernovae," which implies pre-existing circumstellar ejecta. And occasionally the star survived; we call such cases Supernova Impostors, with  $\eta$  Car as the obvious prototype. Equally embarrassing, a few SN events had precursor outbursts, which



seemed paradoxical in the textbook view of supernovae. One supernova in 2012, for instance, already had the name SN 2009ip!

Few researchers believe that any one instability mechanism produced all the eruptions that I've mentioned. Several types probably co-exist: (1) Core-collapse SNaE that had unusual extended envelopes when they exploded; (2) other core phenomena, mostly but not entirely related to nuclear processes; (3) the Demon mentioned earlier, a hypothetical set of radiative/fluid instabilities that can arise when  $L/M > 0.5 (L/M)_{\text{Edd}}$ ; (4) binary interactions, mass transfer, and/or mergers; and (5) whatever we haven't thought of. Incidentally, number 4 is frequently offered as a panacea, but the statistics make that very unlikely. Here let me emphasize a generality that hasn't been widely publicized: Since all these conjectural types of eruption share the same radiative outflow physics, *they look alike* when viewed from outside.

As you might guess, the situation has become too confused for a newcomer to learn easily. Some basic fallacies have propagated in the literature. For instance, most supernova specialists assume that progenitors of Type II<sub>n</sub> must be LBVs, based on faulty logic. (That idea *may* be true, but the evidence cited for it has bad premises.) Many recent authors have applied the term LBV to stars that might belong to that class but are unproven, and to other stars that *don't* belong. Big evolutionary differences between luminous and less-luminous LBVs are seldom acknowledged [5]. Various explain-all “models” consist mainly of words, cartoon sketches, and/or computer runs with many unadvertised assumptions. Reciting their defects would fill many pages. Thus, I earnestly advise everyone to be wary of groupthink – and equally wary of claims that some paper has revolutionized the topic.

Since this is an account of some concepts, and not of the literature, few papers will be cited here. For general background see articles by many authors in [6], and older references in [2] – a review which, amazingly, has not been superseded nor seriously disproven after 22 years (except that it said too little about rotation).

## 2. Radiative physics in a giant eruption

Let's begin with a clear definition. A stellar “giant eruption” is a *super-Eddington mass outflow*, driven by continuum radiation pressure. It is not driven by a shock wave, though shocks may propagate through the flow. It's opaque, so the photosphere is located at a fairly large radius in the outflow. The eruption persists for months or years, much longer than any relevant dynamical timescale. It is quite likely to be non-spherical, e.g. the famously bipolar case of  $\eta$  Car. The word “eruption” is especially apt in some models that behave like geysers, with instability propagating inward while expelling mass outward [2]. Standard large LBV outbursts are not giant eruptions, but they have physical similarities.

We often mention the Eddington parameter  $\Gamma = L/L_{\text{Edd}}$ , where  $L_{\text{Edd}} \approx 4\pi cGM/\kappa$ . Most of the opacity  $\kappa$  is due to Thomson scattering, but the small absorption opacity determines the size of the photosphere (see below). Eta Car's great eruption had  $\Gamma \sim 2$  to 10, but SN 2011ht and SN 2009ip had  $\Gamma > 50$ . Occasionally it is claimed that such large values cast doubt on the entire concept. In fact, however, the basic outflow math for  $\Gamma \rightarrow \infty$  is not much different from  $\Gamma \sim 4$ . The star's mass  $M$  then has little effect and everything depends on  $L$  and on the sonic point where the flow originates; since higher eruption luminosities generally have larger size scales, the outflow speeds usually remain below 1000 km s<sup>-1</sup> even if  $\Gamma > 50$ .

In principle a giant eruption can originate in more than one way. The Demon instability mentioned above, for example, might be an “opacity-modified Eddington limit” affair not far below the star's photosphere, or (more likely) it may involve strange-mode instabilities in the notorious high-opacity layers where  $T \sim 3 \times 10^5$  K [2]. Either way, a lot of extra radiation cannot escape without pushing the outer layers. But a core-collapse SN can also become a giant

eruption. Initially, of course, a SN blast wave occurs. Normally it produces a bright display when it reaches the star’s surface. But suppose the star is surrounded by a large opaque envelope 1000 times as dense as an ordinary stellar wind – something resembling the wind that  $\eta$  Car had 70 years ago. It’s easy to show that photons then diffuse outward ahead of the blast wave. (See, e.g., [10]. Supernova enthusiasts call this phenomenon “shock breakout,” but it’s really photon breakout.) The diffusing radiation accelerates a giant eruption that precedes the blast wave. The shock doesn’t reach the outflow’s photosphere until a time well after the peak brightness.

Logically, this account of a giant-eruption SN transfers the problem to *why* that dense circumstellar stuff was there. It requires a precursor outflow, a less luminous giant eruption in the last few years before the main explosion. But this seems counter-intuitive, because the tiny pre-SN core with its rapid nuclear timescale is not supposed to know about the star’s outer layers, and vice-versa. This looks like evidence that the Demon lives in the core of the star, rather than the outer layers as some of us have usually supposed. But if that’s true, then why is there an LBV instability strip in the HR diagram, representing only the outer layers? And why does it explain the HRD’s upper limit so nicely? (See [2]). Are there two different Demons? Or more? These are among the biggest questions in stellar astrophysics, partly because no one has a credible answer yet.

Unfortunately a super-Eddington flow is very difficult to calculate, because 3-dimensional effects may be crucial. The ejected mass and velocities in  $\eta$  Car’s giant eruption don’t match simple 1-D outflow calculations [7,8]. This shouldn’t surprise us, since it’s conceptually “a light fluid pushing a heavy one” à la Rayleigh-Taylor. R-T instabilities within a star imply convection, but a giant eruption is a supersonic outflow. Likely result: local mass concentrations form and photons escape preferentially along the easiest paths between blobs – thus reducing the effective  $\kappa$  so far as radiative acceleration is concerned. Indeed the ejecta around  $\eta$  Car show obvious granulation with reasonable size scales. This phenomenon in a super-Eddington flow has been called “porosity” [8], though “granulation” may be a better term depending on the topology of the mass condensations. In order to avoid fresh 3-D calculations for each individual eruption, *we need a general, albeit rough, empirical prescription* based on many numerical simulations – in more or less the same spirit as mixing length theory for convection. (Some authors have recently asserted that 1-D models work better than I said above, see, e.g., [9]; but if this is true, it needs to be confirmed by 3-D investigations.)

Next let me say something about observed continuum slopes and emission lines. Giant eruptions, LBV eruptions, and other mass outflows typically have apparent temperatures between 7000 and 10000 K at maximum brightness [2]. This fact is a consequence of opacity physics, and does not imply that the outbursts had similar causes. The average temperature of escaping radiation represents the “thermalization depth” where  $\sqrt{(3 \tau_{\text{tot}} \tau_{\text{abs}})} \sim 1$ . A crucial fact is that opacity decreases rapidly below  $T \sim 7500$  K, and *very* rapidly below 6500 K. This leads to some interesting generalities for a wind or outflow with a given luminosity [11]. First, a moderate mass-loss rate can produce apparent temperatures around 8000 K, defined in a particular way. But reducing that to 7000 K requires a large density and mass-flow rate; 6000 K implies a relatively huge rate; and lower photosphere temperatures are unlikely in almost all cases. Since temperatures in that range also have bolometric corrections near zero, it is entirely natural that opaque outflows of all kinds often look like  $T \sim 7500$  K at maximum brightness.

Here’s an elegant consequence for emission lines. With realistic opacities, a wind’s continuum photosphere (a.k.a. thermalization depth) usually occurs at Thomson scattering depth  $\tau_{\text{sc}} \sim 2$  to 4. Emission lines are formed mostly in the diffuse outflow outside that radius, i.e. in regions where  $\tau_{\text{sc}} \sim 1$  to 3. This is the range where Thomson-scattered line wings are apparent, recognizable, and moderate – just like the spectra of the best-observed giant eruptions (e.g. [12,13]). *When we see moderate Thomson-scattering wings on the Balmer emission lines, with*

*a visual continuum slope like  $T \sim 7000$  to  $15000$  K, then we're probably looking at a super-Eddington flow.*

At this point I feel bound to warn against a particular spectroscopic fallacy: stellar spectral types applied to opaque winds. Casual analogies such as “reminiscent of an F-type supergiant” can be justified, but formally *one should not assign a stellar spectral type to the absorption features of an opaque outflow*. There are good reasons for this caveat. Imagine, for instance, a star with  $T_{\text{eff}} = 6500$  K, compared to an opaque wind with the same photosphere temperature. The star's atmosphere has practically no material with  $T < 5200$  K, but outer parts of the wind can have  $T < 4500$  K. Hence the wind can form absorption lines much cooler than anything in the star's spectrum. See the dispute in refs. [14] vs. [15]; contrary to published claims, the light-echo spectrum of  $\eta$  Car's great eruption agreed reasonably well with expectations.

We now have a sizable fund of excellent data on LBVs and related stars,  $\eta$  Car and other supernova impostors, and on giant-eruption supernovae; observers have done their job well. But theorists have given this topic far less attention than it deserves. As I implied earlier, *this subject is relatively unexplored territory* for theory.

## References

- [1] Humphreys R M and Davidson K 1979 *Astrophys. J.* **232** 409-420
- [2] Humphreys R M and Davidson K 1994 *Publ. Astron. Soc. Pac.* **106** 1025-1051
- [3] Fullerton A W, Massa D L and Prinja R K 2006 *Astrophys. J.* **637** 1025-1039
- [4] van Dyk S D and Matheson T 2012 *Eta Carinae and the Supernova Impostors* **384** 249-274
- [5] Humphreys R M, Weis K, Davidson K and Gordon M S 2016 arXiv:1603.01278
- [6] Davidson K and Humphreys R M (eds) 2012 *ASSL 384, Eta Carinae and the Supernova Impostors* (New York: Springer)
- [7] Shaviv N 2000 *Astrophys. J.* **532** L137-L140
- [8] Owocki S and Shaviv N 2012 *Eta Carinae and the Supernova Impostors* **384** 275
- [9] Quataert E, Fernandez R, Kasen D, Klion H and Paxton B 2015 arXiv:1509.06370
- [10] Margutti R *et al* 2014 *Astrophys. J.* **780** 21
- [11] Davidson K 1987 *Astrophys. J.* **317** 760-764
- [12] Dessart L, Hillier D J, Gezari S, Basa S and Matheson T 2009 *Mon. Not. R. Astron. Soc.* **394** 21-37
- [13] Humphreys R M, Davidson K, Jones T J, Pogge R W, Grammer S H, Prieto J L and Pritchard T A 2012 *Astrophys. J.* **760** 93
- [14] Davidson K and Humphreys R M 2012 *Nature* **486** E1
- [15] Rest A *et al* 2012 *Nature* **482** 375-378