"Outstanding Problems in Massive Stars"
Workshop in St. Paul, October 2012

Eruption Photospheres and How to Use Them

or,

Eta Car's eruption seems OK despite what you've heard, but some SN IIn's and Impostors may be less fortunate

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> During this workshop it became evident that some classic features of existing data are being neglected or misconstrued, while, also, some elementary fallacies have induced needless confusion. Therefore most of these notes and comments were prepared and shown during the meeting. Other remarks were added later.

1. The problem

When a stellar outflow is dense enough to be opaque, naturally its photosphere and color temperature depend on the mass-loss rate. The relevant physics is almost alike for extreme LBV eruptions, SN impostors, Type IIn SNae, etc. We can use the emergent continuum to estimate densities and size scales, and some of these may conflict with publicized interpretations of Type IIn and/or Impostor events. I've prepared these notes because this absolutely essential subtopic appears to be surprisingly unfamiliar among many current researchers. It may have been more widely recognized 20 years ago.

Below are three parts: First, the physics problem. Second, recent misunderstandings in the notorious case of Eta Carinae, and why they matter. Third, the oft-ignored implications for SNae IIn and logically related objects such as SN 2011ht. Most details are omitted.

2. Applicable physics -- fairly basic stuff

In the regions that determine an opaque stellar outflow's appearance, Thomson scattering dominates the violet-to-near-IR opacity. Therefore the emergent continuum originates chiefly at locations where the thermalization depth is near unity: $\tau_{\mathrm{eff}} \approx \sqrt{(3\,\tau_{\mathrm{tot}}\,\tau_{\mathrm{abs}})} \approx 1$. Since the temperature there characterizes the observed continuum, we can reasonably call this zone a photosphere. Higher mass outflow rates $\Rightarrow$ larger photospheric radii $\Rightarrow$ lower color temperatures, and the details must be consistent with opacity dependences $\kappa(\rho, T)$. "Outflow" can mean a continuum-radiation-driven wind, an eruptive flow, pre-existing ejecta hit by a shock wave, or some mixure of these concepts.

In 1987 I published a simplified reconnaissance of this problem, ref. [1]. For likely velocity dependences $V(r)$ and hydrogen ionization above 10% or so, the color temperature of the emergent continuum is determined mainly by a parameter $Q \propto |dM/dt|\, V^{-1} L^{-0.7}$ where L is the current luminosity. (Evaluate Q at the photosphere location.) Figure 1 shows the results with assumptions that could be employed 25 years ago:

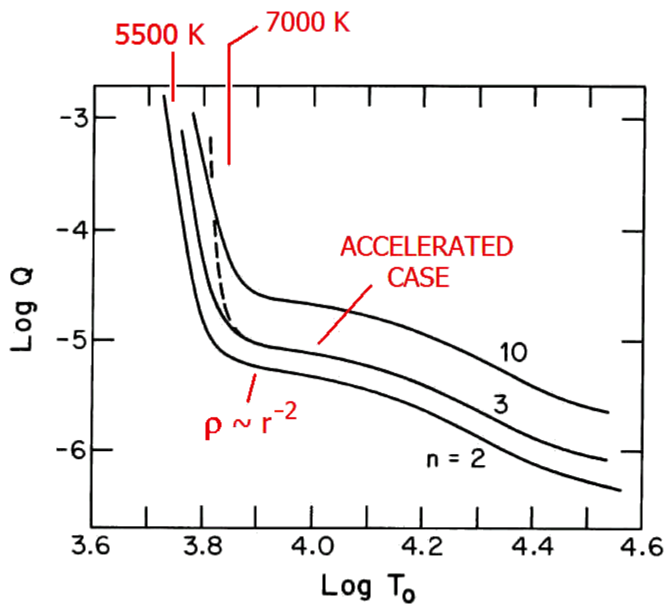

Fig. 1 -- Relation between continuum color temperature of an opaque outflow and its density parameter Q, adapted from ref. [1]. The $n = 2$ curve is most relevant.

T_0 is a sort of color temperature, because "effective temperature" is unsuitable for a diffuse outflow. The curve steepens below 7500 K, so very large outflow rates are required for photospheres cooler than 6000 K. This pseudo-asymptote is due to the rapid decrease of opacity below 7000 K as hydrogen becomes less ionized; in a sense it's analogous to the Hayashi limit. The slope of the curve must decrease above the upper-left corner, allowing $T_0 < 5000$ K for sufficiently high densities, but this detail is unclear because the opacity is hard to assess in that regime. I don't know any applicable analysis newer than [1].

It clearly needs to be updated. Modernized opacities would move the curves downward in Fig. 1, most likely by a factor of the order of 2 in Q. LTE Rosseland opacities were used because multi-frequency NLTE calculations would require immensely more effort; but this defect is probably not serious, since we're not modeling spectral features and the behavior makes sense in terms of basic physics. The simplified radiative transfer was fairly realistic provided the outflow is approximately spherical and $\kappa_{sc} > 3\kappa_{abs}$.

Some people feel that the 1987 paper [1] was somehow erroneous because a few of its remarks about LBVs were (in their opinion) wrong. The main point, however, was Fig. 1 whch is *an approximate solution to a well-defined physics problem*, not a theory to explain LBVs! With suitable caveats, we can apply it to a variety of circumstances.

3. The prototype: Eta Carinae in reality, and beware misinformation

Anyone who works on SNae IIn, giant eruptions, etc., should be expected to know η Car well. Why? -- Because we know more about its behavior than for all the other relevant objects combined. "Peculiar" or not, it's the only available test for some facets of theory. On the other hand, its notoriety often inspires Amazing Discoveries and Grand Theories that don't withstand factual examination. Hence the topic is prone to confusion. For a reasonably sober outline, see many authors' reviews in [2].

A recent development urgently needs to be clarified before it lures researchers down more blind alleys. Rest et al have impressively observed the light-echo spectrum of η Car's Great Eruption c. 1843 (ref. [3]). So far as Fig. 1 allows us to judge, that spectrum looks pretty much as expected, consistent with §2 above. Strangely, however, those authors draw exactly the opposite conclusion: "Light echoes reveal a surprisingly cool η Carinae ..." They say that $T_0 \approx$ 7500 K was predicted but the data imply only 5000 K. Rest et al further assert that this discredits the standard radiation-driven scenario, they advocate a SN-like blast wave instead, etc.; altogether an extraordinary set of claims.

In fact their analysis depends on several elementary fallacies, outlined briefly in ref. [4]. Since the claims would be extremely important if true, and Rest et al have reiterated them at this meeting, I feel obligated to note two fatal defects in more detail than [4].

(a) *Predicted temperature.* Consensus parameters for η Car's Great Eruption imply $\log Q \sim -2.5$ to -4.0 in Fig. 1. The indicated temperature T_0 is thus in the range 5300—6500 K, depending on flow details. How, then, could Rest et al. adopt 7500 K, which gives much higher opacities? Instead of calculating Q and referring to Fig. 1 – an easy operation – <u>they took a single sentence in the 1987 paper out of context:</u>

> *"... The implication seems to be that T_0 cannot fall far below 7500 K even if the mass-loss rate is enormous."*

The context was moderate LBV eruptions with acceleration in the photosphere zones, represented by the sketchy dashed curve in Fig. 1. The figure clearly shows that 7500 K is merely the temperature where the curve begins to turn upward, and *"far below"* meant "below 6500 K." But this case isn't really pertinent here, as the next sentence pointed to a remark which appeared a page later:

> *"As noted earlier, radiative acceleration is difficult for... T_0 < 7500 K ...*
> [but] *this need not be a problem for the great eruption of η Car, because ...*
> [its acceleration probably occurred at smaller radii than the photosphere]."

In other words, for η Car's Great Eruption we should look at the $n = 2$ curve in Fig. 1, not $n = 3$. Admittedly this seems cryptic in an isolated quotation, but the main points are (1) *one should read and understand the whole paper before drawing conclusions,* and (2) *quantitative results are expressed in Figure 1,* not the text.

(The main concern of the latter was to describe the qualitative relation between dM/dt and T_0 -- a fresh result 25 years ago.) Fig. 1 needs to be modernized, but $T_0 < 6500$ K is clearly indicated for η Car's giant eruption. "7500 K" is factually baseless.

(b) *Absorption lines for a given characteristic temperature.* Rest et al based their circa-5000 K "observed" temperature on absorption lines, as though they were classifying a normal supergiant star with a static atmosphere. They employed a doubtful classification technique and an antiquated temperature calibration, see [4] and other refs. therein. More important, though, *the absorption line spectrum of an opaque outflow fundamentally differs from that of a hydrostatic atmosphere.* Moreover, the characteristic temperature T_0 is defined quite differently from a normal star's $T_{\rm eff}$ [1].

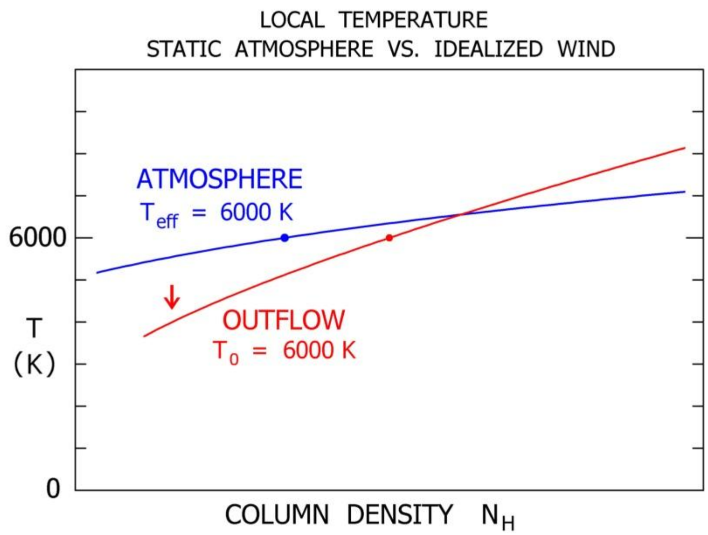

Fig. 2 -- Schematic behavior of column density of material below temperature T, in a normal stellar atmosphere and in an opaque outflow

Fig. 2 illustrates the crucial distinction. Most of the material in and above a normal stellar photosphere has a fairly narrow range of temperatures. Consequently its density distribution is basically exponential in character, resembling $\rho(z) \sim \exp(-z/H)$. By contrast, the relevant part of an opaque wind or eruption outflow is more like a power law, $\rho(r) \sim r^{-n}$, with a broader range of temperatures. In a normal 6000 K star, for example, absorption lines form mainly at temperatures 5000—6000 K. But a wind with T_0 = 6000 K can have appreciable zones below 4500 or even 4000 K (Fig. 2). CN features, for instance, would be unsurprising.

Therefore, if we merely look at absorption lines and pretend it's a regular supergiant atmosphere, we're likely to seriously underestimate T_0. In fact this is what Rest et al appear to have done. *They needed wind models but relied on stellar standards instead.* Hence their "observed" 5000 K should be regarded, at best, as a crude lower limit.

In summary, the light-echo spectrum appears to *confirm,* not contradict, earlier ideas about η Car's Great Eruption. Its characteristic radiation temperature near maximum brightness was most likely in the range 5500 to 6500 K "as expected." The observed spectrum may contain discrepancies that Rest et al didn't recognize, but if so we need a realistic model in order to identify them. Such a model is hard to achieve, because the eruption was manifestly non-spherical.

Rest et al. [3] and a few other authors speculate that Eta's giant eruption involved a SN-like blast wave, i.e., some sort of central explosion. In fact there's no substantial reason to think so, though of course it's hard to prove a negative. The event continued a thousand times longer than the timescales for passage and cooling of a shock. The eruption's ratio of kinetic energy to radiation seems consistent with the standard type of picture, a super-Eddington radiation-driven outflow ([5,6] and refs. therein). Outward speeds up to about 3200 km s^{-1} -- not 6000 km s^{-1} as sometimes alleged -- have been detected in faint material outside the Homunculus ejecta-nebula [7], but the associated mass appears too small to seriously alter the energy budget. The associated emission measures are 4 or 5 orders of magnitude less than the E.M. that the Homunculus would have if it were ionized, and most of the high-speed gas is only about half as fast as the 3200 km s^{-1} maximum observed value. No genuine theoretical model has yet been proposed for this faint high-speed material; but, as remarked in [5], we should not be very surprised if a radiation-driven eruption in a porous medium [6] can produce an outward-accelerating shock. That's not the same thing as a blast wave.

4. Implications for SNae IIn, Impostors, and other objects

A current scenario for some unusual supernovae and/or impostors goes like this: a massive star ejects material in a non-SN eruption, followed by a quieter interval and then a real explosion or an extreme eruption. The latter event becomes very bright when its blast wave reaches the earlier "CS" ejecta. Often this generic picture is labeled "colliding shocks" or "colliding flows" or colliding something. Unfortunately, it isn't clear that the brightening has been modeled properly, using the physics outlined in §2 above. I half-suspect that the fashionable story might need some alteration in order to make the size scales consistent.

The following remarks really just express a hunch, because frankly I haven't done some of the needed analyses. A genuine "model" needs physics with real calculations, not just words and cartoons. Some good papers in this topic (notably [8]) mentioned continuum opacity and thermalization depth, but my impression is that they didn't actually model the photosphere and continuum across the violet-to-near-IR wavelength range. They didn't fully employ information equivalent to Fig. 1. Meanwhile some other oft-cited papers rely on "words and cartoons."

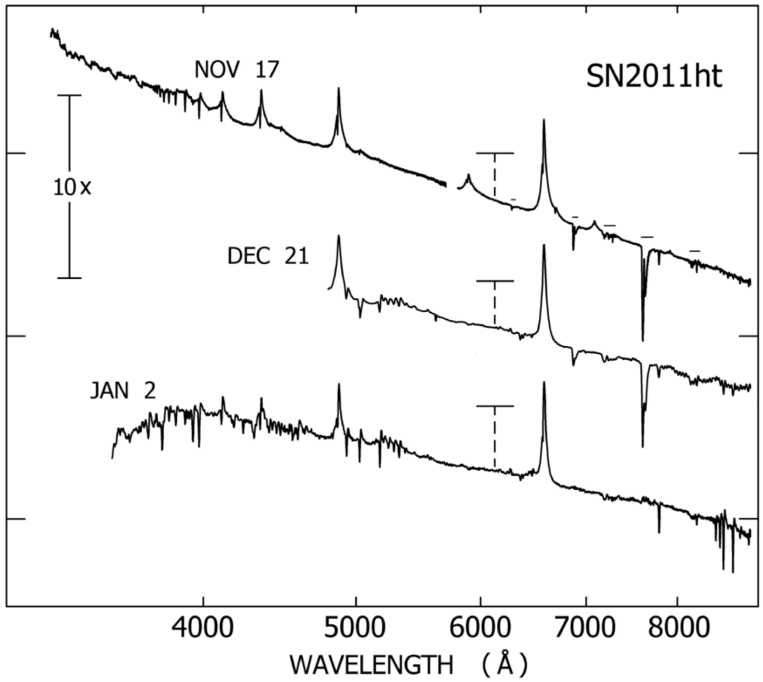

Fig. 3 – Spectrum of SN 2011ht at three different times. Each plot shows log F_λ, adapted from ref. [9]. Attached bars mark approximately the same flux level.

Lately some events have had spectra resembling Fig. 3, which shows the example of SN 2011ht merely because I'm familiar with it [9]. A few deductions --

(a) Most of the violet-to-far-red energy is in the continuum. Therefore we're seeing a photosphere, presumably regulated by the physics outlined in §2. Authors who state that a blast wave has hit some earlier ejecta should verify that their scenario produces a continuum with the observed slope, rather than just emission lines and nebula-like Balmer continua. This is a question of densities, opacities, and size scales.

(b) At maximum brightness (the top spectrum in Fig. 3), the continuum temperature was above 10,000 K. According to Fig. 1, this places a limit on the wind density or mass-outflow parameter Q. In an event of this class, Q varies with time. It may or may not refer to ejecta produced before the current event.

(c) We can use Fig. 1 and the observed brightness to deduce a photosphere radius. This is what worries me, because the result for SN 2011ht was only about 30 AU. That's a size that the observed flow speed would attain in the observed eruption time. A SN blast wave would have reached 30 AU much quicker. In other words, this does *not* straightforwardly match the idea of prior ejecta being hit by a new outflow or a blast wave. It seems easier to reconcile with one continuous outflow, a protracted eruption.

…The parameters for a Type IIn supernova with a similar spectrum aren't much larger. Thus I'm suggesting that "two events" or "two outflows" *may be a misleading idea* in some cases, conceivably in all. Perhaps we should envision, instead, the possibility of one protracted and varying eruption. In every case the theoretical pseudo-photosphere must be checked to see whether broad-band continuum opacities are consistent with the alleged prior-ejecta size scale.

(d) Based on the constraint $\surd\,(3\,\tau_{tot}\,\tau_{abs}) \approx 1$ and the behavior of opacities, we expect the photosphere to have a Thomson-scattering optical depth $\tau_{sc} \sim$ 2--3. Consequently the brightest emission features, formed outside the photosphere in the region $\tau_{sc} \sim 2$, should have moderate Thomson-scattered line profiles of the type illustrated by Dessart et al [10]. Indeed this was the case for SN 2011ht, where a simplified Thomson-scattering analysis led to practically the same outflow parameters as Fig. 1 [9].

Summary: Perhaps the two-event scenario is valid for some supernovae, but it has not truly been demonstrated re. the physics of the observed spectra. This statement particularly applies to some of the brightest observed events, and to some Type IIn SNae. In the future, authors proposing such an interpretation should demonstrate that it is consistent with the physics mentioned in §2 above, including realistic opacities, and should assess the Thomson scattered line profiles if such are present.

References

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[9] Humphreys et al (2012) ApJ 760, art. 93.
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