(PULSATIONAL) PAIR-INSTABILITY SUPERNOVAE

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$\gamma + \gamma \rightarrow e^+ + e^-$; Pair Instability

- Outcome most sensitive to helium core mass
- Pair-instability infrequent or non-existent in solar metallicity stars
- Happens only at high entropy (low density at a given T) and thus in the most massive stars.
## SUMMARY
### PAIR-INSTABILITY SUPERNOVAE

<table>
<thead>
<tr>
<th>He Core Mass</th>
<th>Main Seq. Mass</th>
<th>Supernova Mechanism</th>
<th>without rotation</th>
</tr>
</thead>
<tbody>
<tr>
<td>well known</td>
<td>Poorly known</td>
<td></td>
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</tr>
<tr>
<td>$2 \leq M \leq 32$</td>
<td>$8 \leq M \leq 75$</td>
<td>Fe core collapse to neutron star or a black hole</td>
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<tr>
<td>$32 \leq M \leq 64$</td>
<td>$75 \leq M \leq 140$</td>
<td>Pulsational pair instability followed by Fe core collapse (to a black hole?)</td>
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<tr>
<td>$64 \leq M \leq 133$</td>
<td>$140 \leq M \leq 260$</td>
<td>Pair instability supernova (single pulse, no remnant)</td>
<td></td>
</tr>
<tr>
<td>$M \geq 133$</td>
<td>$M \geq 260$</td>
<td>Black hole</td>
<td></td>
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</tbody>
</table>

Woosley, Blinnikov and Heger (Nature 2007)
Pair instability supernovae can, in principle, be very bright and very energetic (but most are neither).
A wide variety of outcomes is possible (but always less than about $10^{44}$ erg s$^{-1}$)

The light curve is a combination of envelope recombination (RSG and BSG) and radioactivity (He cores)

(e.g., Scannapieco et al 2005; Kasen, Woosley and Heger 2011; Kozyreva et al 2014; Kozyreva and Blinnikov 2015, etc.)
DO THEY HAPPEN?

- Major uncertainty – mass loss as a function of $Z$
- **SN 2007bi** (GalYam et al (2009)) $M_{He} \sim 105M_{\odot}$; 3 - 10 $M_{\odot}$ $^{56}\text{Ni}$ requires substantial reduction in standard mass loss
- Implies the existence of a much larger number of pair and *pulsational pair SN* of lower mass.
• More energetic pulses take a longer time to recur – more energy means expansion to a less tightly bound star.

Since 40 $M_\odot$ is a typical core mass for PPISN, the maximum duration of all pulsing activity is about 10,000 yr. This is an upper bound to the pulsing activity. There will be no PPISN that last longer. Models confirm this.

• An explosion energy of $\sim 4 \times 10^{51}$ erg will unbind the star and make a PISN.
Over time this pulsing activity reduces the entropy...

E.g., 50 $M_\odot$ helium core pulses until 46.7 $M_\odot$ is left then evolves to core collapse.
Central temperature and gravitational binding energy as a function of time (measured prior to iron core collapse for helium cores of 36, 40, 44, 48, 50 and 52 solar masses. As the helium core mass increases the pulses become fewer in number, less frequent, and more energetic.
Faint single pulse events
Normal and structured supernovae
Recurrent bright supernovae
Radio and X-ray Transients

The total mass ejected varies from 0.1 $M_\odot$ at 34 $M_\odot$ to over 8 $M_\odot$ above 56 $M_\odot$
TOTAL ENERGY IN PULSES

- **Pair-Instability SNe** (1 pulse)
- **Sub-luminous SNe**
- **Normal and Superluminous SNe and radio and x-ray transients**
- **Energy vs He core**
- **Total kinetic energy (erg)**
- **Helium core mass (M☉)**
- **< 1 yr**
- **> 1 yr**

The graph illustrates the total energy in pulses, with different categories represented in various colored areas.
Iron Core Probably Collapses to a Black Hole

But the rotation rate can be substantial - milliseconds
No black holes will be born with mass between 52 and 133 solar masses. Many will have masses near 35 – 50 solar masses.

The variation at each mass is due to different assumed mass loss rates in the precollapse star.
Type I (bolometric) light curves for various He/CO core masses. Time is in units of $10^6$ s and the maximum luminosity on the grid is $10^{44}$ erg s$^{-1}$. Similar results would characterize stars produced by chemically homogeneous evolution.
Summary Type I PPI Supernovae bare cores – no rotation

• A variety of transients are possible lasting from days to several thousand years. The optically bright ones last 20 to 100 days, but shorter fainter ones are common.

• Maximum $L$ is a few $10^{43}$ erg s$^{-1}$ if the event is powered only by thermonuclear pulses. Usually quite blue.

• Maximum total radiated energy is $1 – 2 \times 10^{50}$ erg

• Total mass ejected in optically bright events is less than about 8 solar masses

• Probably leave a population of $35 – 50$ solar mass black holes
EXPLOSIONS IN RED SUPERGIANTS (10% Z_0)

70 M_☉ - barely unbind part of the hydrogen envelope. Faint red (3000 K) slow transients - several years. Luminosity less than 10^{41} \text{ erg s}^{-1}, speeds \sim 100 \text{ km s}^{-1}. Mass of envelope depends on mass loss history.

80 M_☉ - entire envelope ejected.
Duration of pulses much less than duration of plateau. Total energy less than 10^{51} \text{ erg}. Faint to normal SN IIp. Peak L \sim 10^{42} \text{ erg s}^{-1}

THESE MAY BE COMMON EVENTS
100 $M_\odot$ – structured light curves with the effects of multiple pulses becoming visible. Shells colliding while SNIIs in progress.

$L_{\text{max}} \approx 0.5 - 1 \times 10^{43} \text{ erg s}^{-1}

Total light $1 - 2 \times 10^{50} \text{ erg}$

90 $M_\odot$ - rather ordinary SN IIp but no radioactive tails.
Now it gets interesting. The helium core has reached 50 solar masses and strong pulses are occurring over a period of years rather than months.

The first pulse ejects the entire envelope in a rather ordinary SN IIP. That will be the case for heavier stars as well. Subsequent pulses eject He and CO rich shells that run into the H-He envelope and make bright long-lasting structured events.
Moving up in mass the intervals between pulses becomes longer and the pulses more energetic. Supernovae can be separated by long intervals during which the star remains shining with a luminosity near $10^{40}$ erg s$^{-1}$.
• Faint long red transients common, $10^{40} – 10^{42}$ erg s$^{-1}$

• Luminosities of $10^{43} – 10^{44}$ erg s$^{-1}$ possible for up to \(~400\) days. He cores that make bright optical transients are in a narrow mass range 48 – 55 solar masses and hence relatively rare.

• Total energy in both light and ejected mass cannot exceed $4 \times 10^{51}$ erg (from pulses alone)

• Preceded by an “ordinary” SN IIp a few years earlier

• Light curves can be highly structured with several major peaks

• More energetic longer events may make radio and X-ray SNe lasting centuries

• Leave a population of 35 – 52 solar mass black holes
Special cases:

1. Superluminous Supernovae – require rapid core rotation

   PPISN only create truly superluminous supernovae \((E_{\text{rad}} \sim 10^{51} \text{ erg})\) when the core experiences a MHD explosion (see also Yoshida et al (2016))

On the left is the explosion of a 110 solar mass model using a piston that imparted \(2.2 \times 10^{51} \text{ erg}\) of kinetic energy to the ejecta. This is in addition to the \(4.6 \times 10^{51} \text{ erg}\) binding energy of the mantle and would require the full rotational energy of a 2 ms pulsar.
R80 – 80 solar mass star with rotation. Total energy $1.8 \times 10^{52}$ erg
Total light $2.1 \times 10^{51}$ erg.

He50 – 50 solar mass helium core. $2.7 \times 10^{51}$ erg explosion (including mantle binding energy). $1.2 \times 10^{51}$ erg of light.
2. Eta Carina and other “Impostors”

- Great eruption 1837 ejected ~15 solar masses with energy \(\sim 10^{50}\) erg. Most ejecta less than \(\sim 1000\) km s\(^{-1}\). Some ejecta \(\sim 4000\) km s\(^{-1}\) (Smith 2008)

- Star still present, \(L \sim 10^{40}\) erg s\(^{-1}\)

- In binary with period 5.54 yr

Possible match:

- 125 M\(_\odot\) star (85 M\(_\odot\) with rotation), 56+-2 M\(_\odot\) He core
- Pulsationally active for several centuries. Total energy \(1.6 \times 10^{51}\) erg
- Ejects 24 M\(_\odot\) of H-He at 1300 km s\(^{-1}\); then 7 M\(_\odot\) of He at 4000 km s\(^{-1}\)
- Currently the remaining CO core is experiencing a Kelvin-Helmholz evolution with \(L = 10^{40}\) erg s\(^{-1}\). Looks like a WR star but isn’t really
- Ejecta are nitrogen rich
- Will collapse to a black hole in the next 1 – 3,000 years
The ejecta is quite asymmetric (Smith 2006) with the forward shock plowing through an envelope of nearly constant density concentration as the reverse shock operates from 10^3 to 10^4 years after the first pulse (i.e., at present epoch) in the ejecta of the Homunculus. The energetic explosion concentrated at latitudes above 45 degrees. Velocities as high as 3500 - 6000 km s^{-1} have been reported, though a more typical speed is 650 km s^{-1}.

Both models leave Wolf-Rayet stars in the present day. Consider the two models, T125A and T125B. Some relevant properties are given in Table 5. Here \( M_{ej} \) is the mass of the primary star in Eta Carinae. Both models explosively eject a mass comparable to the Homunculus. Either a lower mass helium core or larger hydrogen envelope could be behind the lower mass helium core or larger hydrogen envelope.

- T125A: 16.7 M_{\odot}, E_1 = 8.3, t_{1-2} = 70, M_{ej2} = 7.1, E_2 = 8.0, t_{PreSN} = 2650, M_{now} = 51.8
- T125B: 34.0 M_{\odot}, E_1 = 9.6, t_{1-2} = 470, M_{ej2} = 7.4, E_2 = 5.8, t_{PreSN} = 1100, M_{now} = 58.2

T125B fares somewhat comfortably above the lower limit for the observed mass of the secondary object. The mass of the primary star is typically 10^2 - 10^3 M_{\odot}. Most of the mass ejected in the first pulse is envelope, although the mass ejected in the second pulse is helium and carbon. Nitrogen is overabundant in both pulses because of extensive CNO processing. The Homunculus has a metallic mass. Two models do not sus.

The sharp spikes in luminosity are artificial and would be smoothed by mixing in a 2D simulation or by additional opacity. The second outburst in both models happens as the second pulse sweeps over the secondary object. Given the generous error bars of the models, both are measured in years. Neither model is ruled out.

Assuming that the first pulse and the ejection of the envelope occurred around 1837, Model T125A has a second pulse that, within the generous error bars of the models, is measured relative to the second pulse (0 on the plot) and another Great Eruption is due in the next few centuries. It could of course be that the actual pulses were not as energetic however. By now the ejecta of the two pulses would have merged and most of the matter would have a velocity near 2000 km s^{-1}.

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Problematic:

- Observed asymmetry of Eta Carina - Maybe caused by binary companion. Star’s radius expands by factor of several during its last 10,000 years of evolution.

- Large total kinetic energy – $1 \times 10^{51}$ erg, considerably more than inferred from observations.

- How to hide the first SN

- Not enough PPISN to explain all supernova impostors
3. Type IIIn Supernovae

There are too many SN IIIn to explain them all with PPISN, but it is a broad class and may contain PPISN examples

- Circumstellar interaction. Velocities $\sim 1000 – 4000 \text{ km s}^{-1}$
- Irregular light curve. Duration months to a year
- May leave stellar remnants
- e.g., SN 1961v

Smith et al (2009) and discussion therein. 1 decade before SN 1961v the progenitor was observed with a magnitude -12.4 (like eta Car). Maximum may have been a plateau followed by a CSM interaction,
4. Gravitational Radiation

- GW 150914 likely the product of two stars in a binary system with ZAMS 70 and 90 M\(_\odot\) (60 and 70 M\(_\odot\) with rotation). Interestingly at least one of these would have been a PPISN along the way.

- Chemically homogeneous evolution can also produce the black holes with still smaller starting masses, but one would still have been a PPISN (36\(^{+5}_{-4}\) M\(_\odot\))

- GW 150914 shows that at least some stars in this mass range make black holes. Would be good to measure the Kerr parameter – if possible.

- Pile up of black holes 30 – 50 Solar masses. No black hole 52 – 133 solar masses

Woosley (2016)
CONCLUSIONS - PPISN

• Do not happen for solar metallicity, may begin around 0.1 $Z_\odot$

• Great diversity of Type I and II transients expected – from faint blue transients lasting a few days to structured SLSN lasting hundreds of days. Some events may continue for 1000’s of years before the star finally collapses.

• Maximum energy without a central explosion $\sim 4 \times 10^{51}$ erg
  Maximum light $\sim 5 \times 10^{50}$ erg, usually much less.

• May be related to supernova impostors and SN IIn

• Superluminous supernovae from PPISN require at least a partial MHD-core explosion. Probable asymmetry.

• Make black holes from 32 to 52 solar masses. Should be no black holes born in tight binaries with $M = 52$ to 133 solar masses.
CONCLUSIONS - PPISN

- Unless the core explodes the nucleosynthesis of PPISN is confined to light elements, He, C, N, O, Mg. The heavier elements end up in the BHs. Possible implications for abundances in ultra-iron poor stars.