Transients Before Death:
Powering Luminous Events with Explosions Running Into CSM

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Power sources for Supernovae

#1 Radioactive decay
$^{56}\text{Ni} - ^{56}\text{Co} - ^{56}\text{Fe}$ (0.1-1 $M_\odot$)
small $R$ : WD, WR, BSG

#2 Shock-deposited
(thermal energy)
need big initial $R$

Typically:
$E_{\text{rad}}/E_{\text{KE}} \sim 1\%$

$E_{\text{rad}}/E_{\text{tot}} \sim R_*/R_{\text{ph}}$

#3 Circumstellar medium (CSM) Interaction
(shock KE into light - Type II In supernovae)
$E_{\text{rad}}/E_{\text{KE}} \sim 30-50\%$
Efficient conversion of KE $\rightarrow$ Light

\[ L = \frac{1}{2} w V_{SN}^3 = \frac{1}{2} \dot{M} \frac{V_{SN}^3}{V_w} \]

We can observe $V_{SN}$, $V_w$, and $L$, and thus constrain CSM mass.

SNe IIn require several $M_\odot$ of CSM ejected a few to 1000 yr before core collapse.
Can power extremely luminous supernovae with normal ($10^{51}$ erg) core-collapse explosions.

Results in a slow, thin, dense shell, narrow-lined spectra.

LESSON TO BE LEARNED:

Can also power normal-luminosity SN with lower explosion energy (i.e. $10^{50}$ ergs).

Even weaker explosions of $10^{47}$-$10^{49}$ ergs can potentially make intermediate-luminosity transients from a wide variety of weak/failed explosions/eruptions.

All you need is dense CSM and a little energy…
Type II-P subclass:
(Mauerhan et al. 2013)

Type II spectra (nearly identical) with plateau light curves

SN 1994W
SN 2009kn
SN 2011ht

1. Sharp drop in L at 120 days
2. Low inferred $^{56}\text{Ni}$ mass (0.007-0.02 $M_\odot$)
The Crab Nebula and the class of Type IIIn-P supernovae caused by sub-energetic electron capture explosions

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arXiv:1304.0689
FILAMENTS:

$M_{\text{tot}} \approx 5 M_{\odot}$

$V \approx 1200 \text{ km/s}$

$KE \approx 7 \times 10^{49} \text{ erg}$

Abundances:
He-rich, O-poor, low Fe-group

Smith (2003)
FILAMENTS:

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- low Fe-group

Chinese astrologers (SN 1054):
1. Visible in daytime for 23 days
2. Visible at night for 623 days
Progenitor: 10-15 $M_\odot$
RSG

Hester (2008) ARAA

Extended Fast SN Envelope

Crab Nebula Filaments:
Boundary between outer edge of PWN nebula and inner edge of fast SN ejecta

$M_{\text{tot}} \approx 5-7 M_\odot$
5000-10000 km/s
KE $\approx 10^{51}$ erg

Extended Fast SN Envelope

Fe core collapse

10$^{51}$ erg

normal Type II-P

“Standard View”
Progenitor: 10-15 M$_\odot$ RSG

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Crab Nebula Filaments: Boundary between outer edge of PWN nebula and inner edge of fast SN ejecta

Extended Fast SN Envelope

M$_{\text{tot}}$ $\approx$ 5-7 M$_\odot$
KE $\approx$ 10$^{51}$ erg

5000-10000 km/s
Alternative:
Electron-capture Supernova

$10^{50}$ erg

Progenitor:
8-10 $M_{\odot}$
Super-AGB

Nomoto et al. (1982,84,87)

degenerate ONeMg Core

$M_{\text{tot}} \approx 3-6 M_{\odot}$
1200-2500 km/s
KE $\approx 10^{50}$ erg

ecSN:
Low-energy explosion
High He + C, low O abundances
Very low $^{56}\text{Ni}$ yield and low Fe-group abundances

But...

Resulting SN should be faint.

How would we get such a high luminosity from low explosion energy?
Type IIIn-P subclass:

Can be done with $10^{50}$ erg explosion.

Wind density $\sim R^{-2}$

$E_{\text{exp}} = 1.2 \times 10^{50}$ erg
$E_{\text{CDS}} = 7 \times 10^{49}$ erg
$E_{\text{red}} = 5 \times 10^{49}$ erg

Smith (2013)
Type II-P subclass:

Can be done with $10^{50}$ erg explosion.
a) SN progenitor

8-10 Msun super-AGB

equatorial density enhancement

b) SN 1054 - visible in daylight

swept up CDS ~10^6 Lsun from CSM Inter.

c) SN 1054 - reaching end of plateau

pinched waist becomes eq. torus

d) SNR: Aftermath of PWN

CSM: ~2 Msun ~ 10^{15} cm

PWN sweeps into CDS for 1000 yr, R-T Instab.
b) SN 1054 - visible in daylight

swept up CDS
$\sim 10^9$ Lsun from CSM inter.

equatorial density enhancement

c) SN 1054 - reaching end of plateau

pinched waist becomes eq. torus

d) SNR: Aftermath of PWN

crab's thin shell is remnant of CDS

PWN sweeps into CDS for 1000 yr, R-T instab.
c) SN 1054 - reaching end of plateau

- Swept up CDS
- Pinched waist becomes eq. torus
d) SNR: Aftermath of PWN

- Remnant of CDS
- E/W Dark Bays
- "He-rich eq. torus"
- Filaments from heads of R-T
- Crab shell is remnant of CDS
- PWN sweeps into CDS for 1000 yr, R-T instab.
THE CRAB NEBULA:

- **SN 1054 was a Type IIin-P supernova**
  (clear prediction for spectrum of light echoes if we find them)

- **Reconciles low explosion KE (ecSN, \(10^{50}\) ergs) with high luminosity. (ecSN is favored anyway because of abundances.)

- **Evolution of thin swept-up shell in a Type IIin accounts for slow shell of fragmented filaments seen today (especially after 1000 yr of PWN)**

- **Lack of blast wave and outer envelope.**
Power the 10-year Great Eruption luminosity with a $10^{50}$ erg explosion and CSM interaction, as in a Type IIn supernova...
SN 2009ip

- First discovered in Aug 2009 (Maza et al. CBET 1928)
- Re-brightened in July 2010 (Drake et al. 2010, Atel 2897)
- Re-brightened in July 2012 (Drake et al. 2012, Atel 4334)
- Detailed spectra and photometry of 2009 outburst (Smith et al. 2010)
- HST detection of LBV-like progenitor (50-80 $M_\odot$) (Foley et al. 2011)

its 2012 demise

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Smith et al. 2013

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Graphs showing the light curve of SN 2009ip with data points for different epochs and a comparison with other supernovae.

Hα

- Bok 2012 Sept 27 (3rd outburst)
- Keck/DEIMOS 2012 Sept 23 (3rd outburst)
- Bok 2012 Sept 17 (3rd outburst)
- Keck/LRCS 2010 Nov 5 (2nd outburst)
- Keck/LRCS 2009 Sept 22 (1st outburst)

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Smith et al. 2013
IR excess from hot dust – from pre-SN outbursts
(Smith et al 2013, arXiv:1303.0304)
Pastorello et al. (2013) propose that the 2012 event of SN 2009ip was actually a pulsational pair instability ejection event, not a true core collapse SN. Star survived, etc.
Hard to prove definitively… so was SN2009ip really a supernova? It clearly wasn’t a normal supernova, so what constitutes proof?

1. Philosophical comment

2. Kinetic energy $\sim v^2$

$$\frac{1}{2}(M_\odot)(10^4 \text{ km/s})^2 = \text{FOE}$$

3. How many pulsational pair instability events can there be?

SN2006gy 2003ma 1961V
SN2006tf SN2006jc
Quimbies 1994W

And now 2009ip, and 2010mc….

What about all the other Type IIn “supernovae”?
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**PRECURSOR ERUPTIONS:**

SN 2009ip – clear detection of LBV eruptions before SN, plus progenitor star and spectra.

Another case – SN 2010mc (appears to be same as SN2009ip, less pre-SN data; see Ofek et al. 2013)

Another case – SN 2006jc: Outburst detected 2 yr before SN (Type Ibn) at same position (no spectra, and no progenitor star). Pastorello et al. (2007)

**DENSE CIRCUMSTELLAR GAS:**

Type IIn supernovae require eruptive pre-SN mass loss in few years before core collapse.

Huge range of ejected masses (0.1-20 $M_\odot$) and energy (0.001-0.2 FOE).
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**Most significant take-home point:**

✧ CSM in Type II In supernovae and direct detections of precursor events require that some massive stars explode before they explode. Huge range of mass and energy.

**WHY?**

Eruptions a few years (or 1000 yr) before core collapse would suggest nuclear burning instabilities during C, Ne, O, or Si burning.

Check out papers by Meakin & Arnett

✧ Why don’t they all do it?

✧ How does pre-SN event influence structure of the core? Does that influence core collapse?