Wide-Field SN Surveys:
New Regimes of Transient Science

Maria R. Drout
University of Toronto; Carnegie Observatories

Image Credit: Robin Dienel/Carnegie Observatories
Wide-Field Transient Searches

SuperNova Legacy Survey (SNLS)

CALIFORNIA LITHOPHANE STARRY SKY SURVEY (CATALINA)

ASAS-SN

PTF, PS1

Calan/Tololo survey

LOSS

High-z searches (SNLS, SDSS, ESSENCE)

Number of SN

10^2

10^3


Year

(Adapted from Mark Sullivan)
Supernova and Transients

Three pillars of wide-field surveys

1. Identification of Large Samples of Known Classes of SN
2. Discovery of Intrinsically Rare Transients
3. Opening of New Regimes for Transients

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Radio
Infrared (Kasliwal+2017)
Ultra-violet...
Supernova and Transients
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Current/Upcoming Surveys

Wide-Field/All Sky
- ASAS-SN
- PS1
- Dark Energy Survey
- ATLAS
- ZTF
- BlackGEM*
- LSST*

Boutique/Specialized Science
- DLT40
- KMTNet SN Survey
- HiTs
- Deeper, Wider, Faster
- K2/TESS
- Survey for Nothing
Supernova and Transients

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Key Question 1:
What are the observed populations, intrinsic rates, and nature of “peculiar” explosive transients present in the universe?
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Key Question 1:
What are the observed populations, intrinsic rates, and nature of “peculiar” explosive transients present in the universe?
“Peculiar” Transients

LSST Observing Strategy White Paper (adapted from Kasliwal 2011)
## “Peculiar” Transients: Observations

<table>
<thead>
<tr>
<th>Observed Transient</th>
<th>Why “peculiar”</th>
</tr>
</thead>
<tbody>
<tr>
<td>Super-luminous SN</td>
<td>Intrinsically rare; prefer low-mass hosts</td>
</tr>
<tr>
<td>Nuclear flares</td>
<td>rare, image subtraction</td>
</tr>
<tr>
<td>Luminous Blue Transients</td>
<td>rapid</td>
</tr>
<tr>
<td>Type Iax SN</td>
<td>faint, somewhat rapid</td>
</tr>
<tr>
<td>Calcium-rich Transients</td>
<td>faint, somewhat rapid</td>
</tr>
<tr>
<td>Rapidly Declining Type I SN</td>
<td>faint, rapid</td>
</tr>
<tr>
<td>Intermediate luminosity optical transients (ILOTs)</td>
<td>very faint</td>
</tr>
<tr>
<td>Luminous red novae</td>
<td>very faint</td>
</tr>
<tr>
<td>Long-lived Type II</td>
<td>Rare. Bias?</td>
</tr>
</tbody>
</table>
Peculiar Transients

Probe different regimes of progenitor systems and explosion mechanisms. Unique means to study uncertain stages of stellar evolution and channels for stellar death.
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Langer N. 2012.
Peculiar Transients

Probe different regimes of progenitor systems and explosion mechanisms. Unique means to study uncertain stages of stellar evolution and channels for stellar death.

<table>
<thead>
<tr>
<th>Binary system</th>
<th>Outcomes with deflagration-detonation-transition</th>
<th>Outcomes without deflagration-detonation-transition</th>
</tr>
</thead>
<tbody>
<tr>
<td>He-rich WD + C/O WD &lt; 0.8 Msol</td>
<td>Shell detonation</td>
<td>Ia supernova (?)</td>
</tr>
<tr>
<td>He-rich WD + C/O WD &gt; 0.8 Msol</td>
<td>Double detonation</td>
<td>SN Ia</td>
</tr>
<tr>
<td>Low-mass He-burning star + C/O WD &lt; 0.8 Msol</td>
<td>Shell DDT</td>
<td>Ia supernova</td>
</tr>
<tr>
<td>Low-mass He-burning star + C/O WD &gt; 0.8 Msol</td>
<td>Shell DDT</td>
<td>Double detonation SN Iab ??</td>
</tr>
<tr>
<td>High-mass He-burning star + C/O WD &lt; 0.8 Msol</td>
<td>Shell DDT</td>
<td>Ia supernova</td>
</tr>
<tr>
<td>High-mass He-burning star + intermediate-mass C/O WD</td>
<td>Shell DDT</td>
<td>Double detonation SN Ia</td>
</tr>
<tr>
<td>High-mass He-burning star + C/O WD &gt; 1.0 Msol</td>
<td>Core DDT</td>
<td>SN Ia</td>
</tr>
</tbody>
</table>

Table Courtesy of Ken Shen
# Peculiar Transients: Theory

<table>
<thead>
<tr>
<th>Theoretical Transients</th>
<th>Science Case(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tidal Disruption Events</td>
<td>quiescent SMBHs; jet physics</td>
</tr>
<tr>
<td>Kilonovae</td>
<td>Gravitational waves; r-process</td>
</tr>
<tr>
<td>Off-axis GRB afterglows</td>
<td>Rates, energy scale; jet structure</td>
</tr>
<tr>
<td>Accretion Induced Collapse</td>
<td>WD physics</td>
</tr>
<tr>
<td>Helium shell detonation (.Ia)</td>
<td>WD accretion, nuclear physics</td>
</tr>
<tr>
<td>Failed supernovae</td>
<td>BH formation; feedback</td>
</tr>
<tr>
<td>Ejection of a stellar envelope</td>
<td>Mass loss; common-envelope</td>
</tr>
<tr>
<td>Mergers</td>
<td>Merger rates; common-envelope efficiency</td>
</tr>
<tr>
<td>Pair instability SN</td>
<td>Explosion mechanism</td>
</tr>
<tr>
<td>...</td>
<td></td>
</tr>
</tbody>
</table>
Peculiar Transients

• What are the observed populations?
• What is their nature?
• What are their intrinsic rates?

What are the implications?
• Stellar evolution, binary interactions, mass loss, ...
• Physics of compact objects, stellar explosions, ...
SN Phase Space
SN Phase Space

Log Luminosity (erg s⁻¹)

Timescale (days)

Luminous and Blue Transients

Rapidly-Declining Type I SN

"Rapid"
Rapidly-Declining Type I SN
Rapidly-Declining Type I SN

Drout et al. (2013)
Spectroscopic modeling finds an ejecta dominated by oxygen.
(Drout et al. 2013, Tauris et al. 2013, Kleiser et al. 2014)
Rapidly-Declining Type I SN
Possibility 1. An Ultra-stripped SN

Many stages where transients occur....

Common envelope contact binary mergers

X-ray transients

Ultra-stripped SNe

Recycled pulsar + Young pulsar

Geodetic precession

NS+NS merger

LIGO sources

Image courtesy of T. Tauris
Secondary explosion leading to a compact binary can be ultra-stripped. (Tauris+2013, Tauris+2015, Suwa+2015, Moriya+2017, ...)

Rapidly-Declining Type I SN
Possibility 1. An Ultra-stripped SN
Rapidly-Declining Type I SN
Possibility 2. Explosions of helium giants lacking $^{56}\text{Ni}$

Kleiser & Kasen 2014; Kleiser et al. 2018a,b
Rapidly-Declining Type I SN

General Lack of Observational Information

- 2-3 known events
- Rates very uncertain (1% of Type Ia rate?)
- Almost no late-time or pre-peak data.
Rapidly-Declining Type I SN
New Observations: iPTF14gqr

De et al. 2018
Rapidly-Declining Type I SN
New Observations: iPTF14gqr

Mej = 0.2 Msun
Ek = 2x10^{50} erg

Extended envelope:
0.01 Msun
500 Rsun

De et al. 2018
Rapidly-Declining Type I SN
New Observations: iPTF14gqr

De et al. 2018

\[ M_{ej} = 0.2 \text{ Msun} \]
\[ E_k = 2 \times 10^{50} \text{ erg} \]

Extended envelope:
0.01 Msun
500 Rsun

He-rich shell:
0.01 Msun
9000 Rsun
Rapidly-Declining Type I SN

New Observations: iPTF14gqr

He star (stable/unstable) RLO. Most He is ejected from the system

Stripped He star + NS
**Intense mass loss leads to expanding envelope.**

iPTF 14gqr: **Ultra-striped SN inside He-rich envelope**

Double NS system

Mej = 0.2 Msun
Ek = $2 \times 10^{50}$ erg

**Extended envelope:**
0.01 Msun
500 Rsun

**He-rich shell:**
0.01 Msun
9000 Rsun

De et al. 2018
SN Phase Space

- Luminous and Blue Transients
- Rapidly-Declining Type I SN
Luminous and Blue Transients

Drout, M. R. et al. (2014)
Luminous and Blue Transients

Sample Properties:

- Luminous
- Blue Colors
- Expanding & Cooling Photosphere
- Spectra Dominated by Continua
- Star forming host galaxies
Luminous and Blue Transients

Sample Properties:

- Luminous
- Blue Colors
- Expanding & Cooling Photosphere
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Implications/Progenitors:

- Shock break out/cooling from extended stellar envelope or dense wind
- Winds/outflows from compact objects (e.g. Kashiyama & Quataert 2015)
Rate of blue, luminous events are 4.7% of the core-collapse rate at z=0.2

Drout, M. R. et al. (2014)
Luminous and Blue Transients

Rapid Transient at 100 Mpc

Known

Unknown

Radio and X-ray Emission
Central Engine?
Shock breakout from a wind?
Continued Interaction?

Observed Mag

 Continued Interaction?

No additional source?

$^{56}\text{Co}$ Decay?
“New” and “Related” Transients

1. PTF09uj (Type II\textsubscript{n}; Ofek+2010)
2. SN1999cq (Type Ibn; Matheson+2000)
3. SN2015U (Type Ibn; Shivvers+2016)
4. LSQ15ccw (Type Ibn; Pastorello+2015)
5. Rapidly-Rising Transients in the SN-SLSN gap (Arcavi+2016)
6. Rapidly-Rising Transients from Subaru Hyper Suprime-Cam (Tanaka+2016)
7. iPTF16asu (Type Ic-BL; Whitesides+2017)
9. HiTSs transient, CSS transient, LSQ transient, ZTF object
10. DES Sample (Pursiainen et al. 2018)
11. AT2018cow (everyone...2018)
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Mass Loss/Interaction
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SN/Engines
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AT2018cow
The Best Observed Case

Margutti+2018
AT2018cow
The Best Observed Case
**AT2018cow**

The Best Observed Case

- Engine
- CSM
- Hydrogen/helium
- Low $M_{\text{Ni}}, M_{\text{ej}}$

### Table 2. Central X-ray “Engine” Models for AT2018cow

<table>
<thead>
<tr>
<th>Model</th>
<th>Ejecta Mass/Velocity</th>
<th>Engine Timescale</th>
<th>CSM?</th>
<th>He?</th>
<th>H?</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>NS-NS Merger Magnetar</td>
<td>X</td>
<td>✓</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>1</td>
</tr>
<tr>
<td>WD-NS Merger</td>
<td>✓</td>
<td>✓</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>2</td>
</tr>
<tr>
<td>IMBH TDE</td>
<td>✓</td>
<td>Maybė†</td>
<td>X</td>
<td>✓</td>
<td>✓</td>
<td>3</td>
</tr>
<tr>
<td>Stripped-Envelope SN + Magnetar/BH</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>Maybe</td>
<td>X</td>
<td>4</td>
</tr>
<tr>
<td>Electron Capture SN + Magnetar</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>5</td>
</tr>
<tr>
<td>Blue Supergiant Failed SN + BH</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>6</td>
</tr>
<tr>
<td>SN + Embedded CSM Interaction</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>7</td>
</tr>
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Pre-Supernova Mass Loss

Margutti et al. (2014)

[Nathan Smith 2016, Supernova Handbook]
Enhanced Mass Loss in “Normal SN”

Flash Spectroscopy

Gal-Yam et al. 2014.
Enhanced Mass Loss in “Normal SN”

Early Light Curves

Morozova, Piro, & Valenti 2017, 2018
Enhanced Mass Loss in “Normal SN”
Early Observations couple with radio/X-ray

Enhanced Mass Loss in “Normal SN”
Early Observations couple with radio/X-ray

What is the prevalence and extent of enhanced pre-SN mass loss?

How Ubiquitous?

Light Curve Modeling:

Flash Spectroscopy:

Morozova, Piro, & Valenti 2018
see also Asfari, Drout et al., 2018

Kazov et al. 2016
see also Hozzeinzadeh et al. 2018
SLSN; Nicholl+2015

Partially Stripped; Drout+2018

Fully Stripped; Drout+2016

Long-GRBs; Type Ibn...
Tangential/Technical Open Question:
How well do we understand early SN light curves?
How accurately can we pull information from them?
Why does this matter?

Pre-explosion structure of the star
Pre-explosion spin rate of the stellar core

Quataert & Shiode 2012; Shiode & Quataert 2014; Smith & Arnett 2014; Fuller et al. 2015; Fuller 2017, Fuller & Ro 2018
Why does this matter?

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Pre-explosion spin rate of the stellar core

Quataert & Shiode 2012; Shiode & Quataert 2014; Smith & Arnett 2014; Fuller et al. 2015; Fuller 2017, Fuller & Ro 2018
Why does this matter?

T. Sukhbold et al.
Testable Predictions

Fuller (2017)

Kochanek et al. (2017)
Supernova and Transients

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Key Question(s) 3:
What stars explode (or not) as supernova?
How does this, and their explosion properties, change with environment?
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What stars explode (or not) as supernova? How does this, and their explosion properties, change with environment?
Progenitor -> Compact Object?

T. Sukhbold et al.
Observational Lack of High Mass Progenitors

Eldridge, et al. (2013)
Bulk Statistics
Probes of the Underlying Stellar Population

Graur et al. (2017)
Bulk Statistics

Delay – Time Distribution

Zapartas et al. (2017)
Unsolved Problems
In Time Domain Astronomy

What are the observed populations of “peculiar” explosive transients present in the universe?

What is the behavior of massive stars immediately preceding core-collapse?

What stars explode (or not) as supernova?