Illuminating Discoveries From Transient Surveys

Robert Quimby (Caltech)

GWPAW, Milwaukee, 2011 Jan 27
A Tale of Two Surveys

Robert Quimby
ROTSE–III Surveys

- **TSS/RSVP**
  - 0.45-m ROTSE–IIIb telescope
  - 1.85 X 1.85 degree FoV
  - Began in Fall ’04
  - 100–300 square degrees
  - 1–3 day cadence, $M_{\text{lim}}$ 18 to 19
  - Target selection without (intentional) host bias
  - High quality spectra of all transients
  - 90+ SNe to date including 6 LSNe
  - Only spectroscopically complete Transient Survey
ROTSE–III Surveys

“We have previously not encountered a supernova spectrum having these characteristics”
--A. V. Filippenko et al., IAU Circular 8639, regarding SN 2005la

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Palomar Transient Factory

Link together the wide field survey potential of the 48”, multi-band photometric screening with the 60”, and spectroscopic typing by the 200” telescopes

Explore known transients in new ways
Hunt for new transient classes
Palomar Transient Factory

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P48 (survey telescope)
P60 primary follow-up telescope

Thursday, January 27, 2011
A Big 0.024%
A Big 0.024%

- HST
A Big 0.024%
PTF/ROTSE Follow-Up

IceCube
- high energy neutrino telescope
- 3 events so far (~10/year)
- ~1.5 deg error circles
- PTF actively investigating recent alert

LIGO+
- PTF followed up one trigger covering about 10 fields
- Now offline for upgrade
EM Constraints on SN Explosion Times

- Use well sampled light curve (and spectra) with early detections to estimate explosion date

Quimby et al. 2007; see also Dessart et al. 2008
Supernova Primer

Type II
- key feature: Hydrogen
- $M_{\text{peak}} \sim -16.5$ mag
- linked to core-collapse of massive ($M > 10 \, M_\odot$) stars

Type Ia
- key feature: Si II 6355
- $M_{\text{peak}} \sim -19.5$ mag
- linked to TNR in white dwarf stars

Type Ib/c
- "default" class
- $M_{\text{peak}} \sim -18.0$ mag
- linked to core-collapse of massive stars with stripped envelopes

Expansion velocities:
~ $10^4$ km/s
P-Cygni Profile:
- broad emission with blue shifted

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Transient Phase Space

Rau et al. 2009

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Faint and Fast: PTF10bhp
Possible Ia?

Kasliwal et al. 2010

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Faint and Slow: PTF10fqs

Kasliwal et al. 2010b
Host Galaxies of PTF SNe
(Core–Collapse Supernovae)

Arcavi et al. 2010

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Super/Over/Extremely/Very Luminous Supernovae

SNe with peak absolute (optical) magnitudes brighter than -21 are Luminous Supernovae (LSNe)

Richardson et al. 2002
SNe with peak absolute (optical) magnitudes brighter than -21 are Luminous Supernovae (LSNe)
SN 2006gy

- Peak absolute magnitude nearly -22
- Brighter than -21 mag for ~100 days
- Integrated light $>10^{51}$ erg
Pair-Instability SNe

First Proposed in the 1960’s (Rakavy et al. 1967; Barkat et al. 1967)

Massive stars are supported by radiation pressure

At high temperatures, photons are created with $E > e^+e^-$

Losses to pair production soften the EOS, and lead to instability

Expected fate of the first (low metal, high mass) stars
SN 2006gy Late-Time Light Curve

The evolution of the bolometric luminosity of SN 2006gy during the first 800 days after explosion. Optical data are shown as black circles, and NIR data are shown as red squares. The dashed line shows the expected decline if the luminosity were powered by 2.5 $\times 10^{56}$ $^{56}$Co decay alone. The flat nature of the light curve indicates that excess. We consider four possibilities for heating the dust: (1) radioactive heating from $^{56}$Co decay, (2) collisional excitation of the dust that may have been heated via collisions with the expanding material in the SN cavity, at which point collisional excitations of the dust may explain NIR emission.

The large peak luminosity of SN 2006gy, $8 \times 10^{56}$ ergs, was observed near day 100, and that the combination of the peak luminosity and the radioactivity-powered luminosity of an SN, assuming 100% radioactive heating, could dominate the IR emission, in which case the luminosity could be significantly higher than the expected light curve from 2.5 $\times 10^{56}$ $^{56}$Co decay dominates over radioactive heating from a minimum of 2.5 $\times 10^{56}$ $^{56}$Co.

The optical and NIR luminosities are from Smith et al. (2008b). The early-time measurements (250 days) come, however, been excluded; see also Smith et al. (2010). Miller et al. (2010). The large peak luminosity of SN 2006gy (Ofek et al. 2009) showed that the combination of the peak luminosity and the radioactivity-powered luminosity of an SN, assuming 100% radioactive heating, could dominate the IR emission, in which case the luminosity could be significantly higher than the expected light curve from 2.5 $\times 10^{56}$ $^{56}$Co decay dominates over radioactive heating from a minimum of 2.5 $\times 10^{56}$ $^{56}$Co.

The optical luminosity at times $\gtrsim 400$ days after an artificial reduction of the total ejecta mass from their evolutionary calculation, was able to reproduce the late-time NIR luminosity is not accounted for in either the general pulse SN models or the artificial model of Nomoto et al. (2007). The possibility of a PISN was first invoked to explain the large peak luminosity of SN 2006gy (Ofek et al. 2009). This scenario would have required the production of $\gtrsim 0.98$ mag (100 day) $^{56}$Ni at times $\gtrsim 400$ days. The early-time measurements (250 days) come, however, been excluded; see also Smith et al. (2010). Miller et al. (2010). The large peak luminosity of SN 2006gy, $8 \times 10^{56}$ ergs, was observed near day 100, and that the combination of the peak luminosity and the radioactivity-powered luminosity of an SN, assuming 100% radioactive heating, could dominate the IR emission, in which case the luminosity could be significantly higher than the expected light curve from 2.5 $\times 10^{56}$ $^{56}$Co decay dominates over radioactive heating from a minimum of 2.5 $\times 10^{56}$ $^{56}$Co.

This model of Woosley et al. (1983) was heated via collisions with the expanding material in the SN cavity. Even if there are ejecta traveling at more typical SN velocities, this model of Woosley et al. (1983) was heated via collisions with the expanding material in the SN cavity. Even if there are ejecta traveling at more typical SN velocities, this model of Woosley et al. (1983) was heated via collisions with the expanding material in the SN cavity. Even if there are ejecta traveling at more typical SN velocities, this model of Woosley et al. (1983) was heated via collisions with the expanding material in the SN cavity. Even if there are ejecta traveling at more typical SN velocities, this model of Woosley et al. (1983) was heated via collisions with the expanding material in the SN cavity.
SN 2006gy Late-Time Light Curve

Miller et al. 2010

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Ejecta run into surrounding material (progenitor wind, shells, etc.)

Smith et al. 2008

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SN 2005ap

- R = 23.5 mag host (not seen)
- Peak observed mag = 18.1 (unfiltered)
- Observed light curve rise = 7 days
- Estimated rise time >20 days?
LSN-Ic Spectra
PTF09cnd: Late-Time Spectra
PTF09cnd: BB Comparison

SN 2008D
- Discovered by SWIFT during shock breakout (Soderberg et al. 2008)
- Type Ib/c
- Compact progenitor ($R_\star \sim R_\odot$)

SN 2008es
- Discovered by ROTSE–III (Gezari et al. 2009)
- Type II (very luminous, $M_{\text{peak}} < -22$)
- Likely extended progenitor ($R_\star > 5000 R_\odot$)
Shell Scenario

- outer shell expanding at a few 1000 km/s
- energy injected from within
Pulsational Pair-Instability SNe

Woosley et al. 2007

<table>
<thead>
<tr>
<th>Helium Core</th>
<th>Number Pulses</th>
<th>Energy Range</th>
<th>Interval Range</th>
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<tbody>
<tr>
<td>$M_{\text{sun}}$</td>
<td>6</td>
<td>$10^{51}$ erg</td>
<td>years</td>
</tr>
<tr>
<td>48</td>
<td>6</td>
<td>.11 - 2.4</td>
<td>.02 - 0.26</td>
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<tr>
<td>51</td>
<td>4</td>
<td>.44 - 3.7</td>
<td>0.09 - 0.9</td>
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<tr>
<td>52</td>
<td>4</td>
<td>.94 - 3.1</td>
<td>.01 - 3.0</td>
</tr>
<tr>
<td>54</td>
<td>3</td>
<td>2.1 - 3.2</td>
<td>0.03 - 12</td>
</tr>
<tr>
<td>56</td>
<td>3</td>
<td>1.3 - 3.3</td>
<td>.01 - 110</td>
</tr>
</tbody>
</table>

Woosley et al. 2007

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Magnetar Model

\[ E_p = \frac{I_{ns} \Omega_i^2}{2} = 2 \times 10^{50} P_{10}^{-2} \text{ ergs,} \]

\[ t_p = \frac{6I_{ns} c^3}{B^2 R_{ns}^6 \Omega_i^2} = 1.3 B_{14}^{-2} P_{10}^2 \text{ yr,} \]

\[ L_{\text{peak}} \sim \frac{E_p t_p}{t_d^2} \sim 5 \times 10^{43} B_{14}^{-2} \kappa_{\text{es}}^{-1} M_5^{-3/2} E_{51}^{1/2} \text{ erg s}^{-1} \]

Kasen & Bildsten 2010

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## LSNe (Candidates) from PTF

### Table of LSNe Candidates from PTF

<table>
<thead>
<tr>
<th>Name</th>
<th>Notes</th>
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<tbody>
<tr>
<td>PTF09uy</td>
<td>LSN-IIIn</td>
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<tr>
<td>PTF09atu</td>
<td>LSN-Ic</td>
</tr>
<tr>
<td>PTF09cnd</td>
<td>LSN-Ic</td>
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<tr>
<td>PTF09cwl</td>
<td>LSN-Ic</td>
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<td>PTF10bfz</td>
<td>BL-Ic</td>
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<td>PTF10bjp</td>
<td>LSN-Ic</td>
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<td>LSN-Ic</td>
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<td>PTF10fel</td>
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<td>PTF10xee</td>
<td>LSN-Ic?</td>
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<td>PTF10vqv</td>
<td>LSN-Ic</td>
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</tbody>
</table>

### Diagram

- **LSN-Ic**: 50%
- **LSN-IIIn**: 40%
- **Bright BL-Ic**: 10%

**Observed numbers--not volumetric rates!**

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Redshift Distributions

TSS (ROTSE)

<table>
<thead>
<tr>
<th>Class</th>
<th>Rate (# Mpc$^{-3}$ yr$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type Ia</td>
<td>$3 \times 10^{-5}$</td>
</tr>
<tr>
<td>CCSN</td>
<td>$1 \times 10^{-4}$</td>
</tr>
<tr>
<td>SLSN</td>
<td>$(&gt;?) 3 \times 10^{-7}$</td>
</tr>
</tbody>
</table>
ROTSE SN Host Galaxies

[Graph showing the relationship between log(O/H) + 12 and Stellar Mass (M_☉) with data points labeled T, indicating Tremonti et al. members, and + = Levesque et al. z<0.3 GRB hosts. The graph includes preliminary data and is labeled with Galaxy names such as ρ312031, ρ60218, and ρ50826.]
SN 2007bi: The PISN Case

- Optical light curve decay rate consistent with the production of \( \sim 7 \, M_\odot \) of \(^{56}\text{Ni}\)
- Iron abundance in nebular spectra also consistent with the decay of \( \sim 4-7 \, M_\odot \) of \(^{56}\text{Ni}\)
SN 2008es

Gezari et al. 2009; see also Miller et al. 2009

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It's Full of (Time Variable) Stars