Echoes of Ancient Supernovae in the Large Magellanic Cloud

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Why should you care about echoes?

• Light scattered by dust ("echoes") have been observed from a few recent supernovae: 1986G, 1987A, 1991T, ...

• Probes the spatial 3-D structure of the dust

• SN light echoes should in principle be visible hundreds to thousands of years after explosion

• Light echoes from ancient supernovae could allow us to observe the same light seen by Tycho and Kepler

• By taking spectra of light echoes, we may type ancient supernovae directly

• Light echoes offer the only opportunity to study both the initial explosions and remnants in the *same* supernovae
The SuperMACHO project: A next generation microlensing survey

Primary science goal:
How much do “MACHOs” contribute to the Galactic dark matter halo?
SuperMACHO Survey: Microlensing Survey towards the LMC

- More events
  - CTIO 4m
  - Mosaic Imager: big FOV
  - 150 half nights over 5 years
  - Blocks of 3 months per year
  - One Filter: “VR”

- Spatial Coverage
  - 68 fields, 23 deg$^2$

- Difference Imaging
“False” alerts

Oct. 2001
The Light Echoes of SN 1987A
The Light Echoes of SN 1987A
The Light Echoes of SN 1987A
Geometry of Light Echoes

- Ellipsoids trace out surfaces of constant arrival time
The Geometry of the SN 1987A Light Echoes

Xu, Crotts, & Kunkel (1995)
Light Echo Surface Brightness

\[ B_{SC}(\lambda, t, \phi) = F(\lambda)n_H(r)\frac{c\Delta z}{4\pi r \rho \Delta \rho} S(\lambda, \mu) \]

Simpler parameterization, with assumptions:

\[ \Sigma_2 = \Sigma_1 + (V_{SN,2} - V_{SN,1}) \]

\[ -2.5\log_{10}[r_1 t_1/(r_2 t_2)] \]

\[ -2.5\log_{10}(\Phi_2/\Phi_1) \]
Extracting Light Echoes with NN2: Zero-flux correction

- Single-template difference image
- NN2 image, combined and smoothed

- Combine each year
- Smooth with 3x3 kernel
- http://www.ctio.noao.edu/~supermacho/lightechos/
SN 87A Light Echoes with NN2 Difference Imaging (each season combined and smoothed)

Newman & SuperMACHO collaboration, in preparation
Light Echoes from a source other than SN 1987A?
Light Echoes from Ancient Supernovae in the LMC

- Three distinct light echo groups
- Apparent proper motion: between $0.7c$ and $1.8c$
- R magnitudes between 22.5 and 24.0

For Type Ia SN, assuming dust sheet at $z=150$ pc, same dust density as sheets close to 87A

At 500 yr, $\Sigma_V = 22.5$ mag arcsec$^{-2}$, $\rho = 0.29$ deg (250 pc)

At 1000 yr, $\Sigma_V = 24$ mag arcsec$^{-2}$, $\rho = 0.5$ deg (420 pc)
SNRs Associated with the Light Echoes: Ages

TABLE 1
THE SMALLEST SUPERNOVA REMNANTS IN THE LARGE MAGELLANIC CLOUD

<table>
<thead>
<tr>
<th>SNR Name</th>
<th>Age or Radius</th>
<th>SN Type</th>
<th>Echo</th>
</tr>
</thead>
<tbody>
<tr>
<td>SN 1987A</td>
<td>8 yr</td>
<td>II</td>
<td></td>
</tr>
<tr>
<td>0540 – 69.3</td>
<td>1.5 pc</td>
<td>II</td>
<td></td>
</tr>
<tr>
<td>N157B</td>
<td>1.8 pc</td>
<td>(II)?</td>
<td></td>
</tr>
<tr>
<td>N103B</td>
<td>3.0 pc</td>
<td>Ia</td>
<td>LE3</td>
</tr>
<tr>
<td>0509 – 67.5</td>
<td>3.3 pc</td>
<td>Ia</td>
<td>LE2</td>
</tr>
<tr>
<td>0519 – 69.0</td>
<td>3.6 pc</td>
<td>Ia</td>
<td>LE1</td>
</tr>
</tbody>
</table>

Rest et. al., 2005, Nature, 438, 1132

<table>
<thead>
<tr>
<th>Echo</th>
<th>SNR</th>
<th>Age(yrs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SN 87A</td>
<td></td>
<td>15.9 ± 1.4</td>
</tr>
<tr>
<td>LE1</td>
<td>0519-690</td>
<td>600 ± 200</td>
</tr>
<tr>
<td>LE2</td>
<td>0509-675</td>
<td>400 ± 120</td>
</tr>
<tr>
<td>LE3</td>
<td>0509-687</td>
<td>(860)</td>
</tr>
</tbody>
</table>

CAVEAT: Assumes perpendicular dust sheet

Hughes et. al. (1995)
Light Echoes from a source other than SN 1987A?
Light Echo Spectrum LE2

- Gemini-S GMOS
- Nod&Shuffle Mode
- Light Echo group LE2 (SNR 0509-67.5)
- SN 1998es (Ia) template fitted (integrated, scattered)
Light Echo Spectrum LE2

- Smoothed observed spectrum (blue)
Light Echo Spectrum LE2

- Nugent Ibc template (red)
Light Echo Spectrum LE2

- Nugent IIp template (red)
Light Echo Spectrum LE3
Spectra of all three light echoes
Conclusions

• Light echoes from supernovae are visible hundreds of years after explosion

• Light echoes by themselves allow exploration of three-dimensional structure of dust in nearby galaxies
  • Light echoes of SN 87A in unprecedented detail and depth
  • Extended dust sheet 1 kpc in front of SN 87A

• With spectra of light echoes, we can establish Type Ia/Type II SN rates over baselines of hundreds of years in individual galaxies

• Light echoes offer the only opportunity to study both the initial explosion and its after-effects in the same objects
Future: Historic Galactic Supernovae

<table>
<thead>
<tr>
<th>SN name</th>
<th>Explosion date</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cas A</td>
<td>1680 AD?</td>
<td>SN Ib?</td>
</tr>
<tr>
<td>Kepler</td>
<td>1604 AD</td>
<td>SN Ia or Ib?</td>
</tr>
<tr>
<td>Tycho</td>
<td>1572 AD</td>
<td>SN Ia</td>
</tr>
<tr>
<td>SN 1181</td>
<td>1181 AD</td>
<td>?</td>
</tr>
<tr>
<td>SN 1006/Lupus</td>
<td>1006 AD</td>
<td>SN Ia</td>
</tr>
<tr>
<td>Crab Nebula</td>
<td>1054 AD</td>
<td>SN II</td>
</tr>
<tr>
<td>RCW 86</td>
<td>0185 AD</td>
<td>SN II?</td>
</tr>
</tbody>
</table>
Example Galactic SN: Tycho

- $V_{\text{max}} = -6.5$, distance 3100 pc
- Dust sheet 400 pc in front of Tycho:
  - Surface brightness about $V=22.0$
  - Arcs about 6.5 deg away from SNR
  - Apparent proper motion: 30”/yr
  - Light echo width 30”