Constraints on Cosmic Ray Acceleration Efficiency in Balmer Shocks of the Two Young Type Ia Supernova Remnants in the Large Magellanic Cloud

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Image Credit-Hubble Heritage
Two Shock Structure

- Unshocked Ejecta
- Contact Discontinuity
- Forward Shock
- Reverse Shock
- Shocked Ambient Medium
- Shocked Ejecta
https://youtu.be/jA0v1Mh_Oq8
Balmer-dominated Shocks

Hα spectrum of RCW 86 from Helder et al. 2009
Balmer-dominated Shocks

Hα spectrum of RCW 86 from Helder et al. 2009

- Narrow Hα – collisional excitations of hydrogen entering the forward shock
Balmer-dominated Shocks

- Narrow Hα – collisional excitations of hydrogen entering the forward shock
- Broad Hα – Charge transfer from neutral hydrogen entering the forward shock that exchange their electron with a post-shock proton
Measuring Global Shock Speed

Results from Hovey, Hughes, and Eriksen 2015
Measuring Global Shock Speed

Results from Hovey, Hughes, and Eriksen 2015
Signatures of Efficient CR Acceleration

\[ k_B T_{e,p} = \frac{3}{16} m_{e,p} V_{FS}^2 \]

\[ \beta = \frac{T_e}{T_p} = \frac{m_e}{m_p} \]

Van Adelsberg et al. 2008

Helder et al. 2010

Helder et al. 2010

Helder et al. 2010
Previous Claims of Temperature Equilibration in SNR 0509-67.5

Table 1
Best-fit Parameters for the Hα Lines of both the NE and SW Spectra

<table>
<thead>
<tr>
<th>Parameter</th>
<th>SW</th>
<th>NE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Center narrow (km s⁻¹)</td>
<td>287.0 ± 1.4</td>
<td>286.0 ± 1.5</td>
</tr>
<tr>
<td>Center broad (km s⁻¹)</td>
<td>-342 ± 28</td>
<td>459 ± 220</td>
</tr>
<tr>
<td>FWHM broad (km s⁻¹)</td>
<td>2680 ± 70</td>
<td>3900 ± 800</td>
</tr>
<tr>
<td>Total flux x 10⁻¹⁶ erg s⁻¹ cm⁻² arcsec⁻²</td>
<td>8.6</td>
<td>5.3</td>
</tr>
<tr>
<td>Jh/Jn</td>
<td>0.29 ± 0.01</td>
<td>0.08 ± 0.02</td>
</tr>
</tbody>
</table>

Notes. a Approximate flux calibration based on an observation of a photometric standard star (LTT 2415; Haney et al. 1994) taken on 2010 November 11.

Helder et al. 2010, 2011
SNR 0509-67.5 and 0519-69.0 Longslit Locations
SNR 0509-67.5 FORS2 Spectrum
SNR 0519-69.0 SALT Spectra
Comparing Shock Speeds to Broad Hα Widths

\[ \beta = \frac{T_e}{T_p} \]

- \( \beta = 0.01 \) (black solid line)
- \( \beta = 1.00 \) (red dashed line)

- \( \varepsilon_{CR} = 0\% \) (black dotted line)
- \( \varepsilon_{CR} = 20\% \) (red dotted line)

\[ \varepsilon_{CR} \equiv \frac{\rho_{CR}}{\rho_{0,\text{tot}} V_s^2} \]

Plot showing Hα FWHM vs. \( V_s \) in km s\(^{-1}\) with various labels and data points.
Constraining CR Acceleration Efficiencies

CR ACCELERATION EFFICIENCY LIMITS AND TEMPERATURE EQUILIBRATION RATIOS FOR 0509–67.5 AND 0519–69.0

<table>
<thead>
<tr>
<th>Extraction Region</th>
<th>ϵ_{CR;upper}^{(1)}</th>
<th>β_{upper}^{(2)}</th>
</tr>
</thead>
<tbody>
<tr>
<td>0509–67.5 NE</td>
<td>0.13</td>
<td>0.42</td>
</tr>
<tr>
<td>0509–67.5 SW Outer</td>
<td>0.29</td>
<td>...</td>
</tr>
<tr>
<td>0509–67.5 SW Inner 1</td>
<td>0.28</td>
<td>...</td>
</tr>
<tr>
<td>0509–67.5 SW Inner 2</td>
<td>0.33</td>
<td>...</td>
</tr>
<tr>
<td>0509–67.5 SW Inner 3</td>
<td>0.00</td>
<td>...</td>
</tr>
<tr>
<td>0519–69.0 Slit 1 North</td>
<td>0.21</td>
<td>0.84</td>
</tr>
<tr>
<td>0519–69.0 Slit 1 South</td>
<td>0.35</td>
<td>...</td>
</tr>
<tr>
<td>0519–69.0 Slit 2 North</td>
<td>0.46</td>
<td>...</td>
</tr>
<tr>
<td>0519–69.0 Slit 2 Middle 2</td>
<td>0.19</td>
<td>0.56</td>
</tr>
<tr>
<td>0519–69.0 Slit 2 Middle 1</td>
<td>0.41</td>
<td>...</td>
</tr>
<tr>
<td>0519–69.0 Slit 2 South</td>
<td>0.13</td>
<td>0.38</td>
</tr>
<tr>
<td>0519–69.0 Smith ’91 East</td>
<td>0.66</td>
<td>...</td>
</tr>
<tr>
<td>0509 – 67.5</td>
<td>0.06</td>
<td>0.47</td>
</tr>
<tr>
<td>0519 – 69.0</td>
<td>0.11</td>
<td>0.55</td>
</tr>
<tr>
<td>All Points</td>
<td>0.07</td>
<td>0.25</td>
</tr>
</tbody>
</table>

\[ \epsilon_{CR} = \frac{P_{CR}}{\rho_{0,\text{tot}}V_{SH}^2} \]

\[ \epsilon^* = \frac{P_{CR}}{\rho_{0,\text{ion}}V_{SH}^2} \equiv \frac{\epsilon}{\chi} \]

**SNR 0509-67.5**

ε* < 12%

**SNR 0519-69.0**

ε* < 22%

Full Ensemble

ε* < 14%

NOTE. — (1) - Upper limits at 95% confidence for CR acceleration efficiency assuming no equilibration between electron and ion temperatures (β = 0.01).
(2) - Upper-limit values at 95% confidence for β, unless it cannot be unconstrained between the limits of 0.01 ≤ β ≤ 1.
Comparison to Tycho’s SNR

Smith et al. 1991
Comparison to Tycho’s SNR

• Using hydrodynamic modeling, Slane et al. (2014) concluded that:
  – \( \approx 16\% \) of KE has been converted into relativistic particles
  – \( \approx 11\% \) of these particles have escaped as CRs
  – Diffuse shock acceleration efficiency of 26\%
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<tr>
<th>SNR 0509-67.5</th>
<th>SNR 0519-69.0</th>
<th>Full Ensemble</th>
</tr>
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<tr>
<td>( \varepsilon^* &lt; 12% )</td>
<td>( \varepsilon^* &lt; 22% )</td>
<td>( \varepsilon^* &lt; 14% )</td>
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Comparison to Tycho’s SNR
Conclusions

• Bright BD shocks are regions of minimal CR acceleration efficiencies

• SNRs 0509-67.5 and 0519-69.0 accelerate CRs with significantly lower efficiency than Tycho’s Remnant

• Further work needed to break degeneracy between post-shock temperature ratios and CR acceleration efficiencies