Kinematics of Supernova Remnants

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Thanks to:
Vikram Dwarkadas (U Chic.)
Franz Bauer (PUC Chile)
Tracey DeLaney (WVWC)
SNR Kinematics Overview

"Just don't try to include too much ..."

-- Vikram D.

- General considerations
- X-ray observations summary
- Some specific examples
  - Tycho (Type Ia)
  - SN 1996cr (Core-collapse, very young)
  - Cas A (Core-collapse)
- What I'm not including:
  - Type Ia SNe, GRBs
  - Non-thermal and CR-modified effects
SNR ingredients

- SNe to SNR
  - Interaction of Ejecta with CSM
  - Simple self-similar 1D solutions (power law in r)

- Core-collapse
  - Ejecta: explosion mechanisms break symmetry
    SASI; neutrino-driven; jet-induced; bipolar/equatorial
  - CSM: Massive star mass loss, wind(s); environment (MCs)

- Type Ia
  - Ejecta: Exponential
  - CSM: lower density(?); environment (MCs)
Ejecta: Explosion Models

jet-induced
Wheeler'08

SASI
Blondin'05

neutrino-driven
Hammer'09
CSM : Effect of Mass-loss History

- Cas A W-R phase?
  - "the jury is still out"
- Effects the hydro
  - van Veelen '09
    - RSG, no W-R
    - RSG + 15 k yr.s W-R
Shock-Cloud Interaction

- Dense "clumps"
- Radiative - optical emis.
- ...or... Evaporate
  - Orlando '05 and subsequent papers
Observing the Kinematics

- Requires highest E/dE on Frit's plot
  - velocities: thermal, turbulent, radial
  - accurate to 100 km/s or less
- "kinematics"
  - proper motion - multi-epochs
  - Doppler ("radial") velocity - lines
  - ==> hydro dynamics
  - ==> 3D structure
- Multi-wavelength inputs
  - IR, NIR, optical, UV, EUV

3C 58 optical data
Fesen+ (2008)
Type Ia SNR Results

Table 1 Type Ia SNRs: Summary of X-ray Kinematics.

<table>
<thead>
<tr>
<th>SNR Name</th>
<th>X-ray Measurement(s)</th>
<th>Reference(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>G1.9+0.3</td>
<td>prop.mo’ &amp; Doppler shifts/broad(25 k km s(^{-1}))</td>
<td>Reynolds (2008), Borkowski (HEAD’10)</td>
</tr>
<tr>
<td>Kepler (SN 1604)</td>
<td>prop.mo’</td>
<td>Hughes (1999)</td>
</tr>
<tr>
<td>N103B</td>
<td>little broadening</td>
<td>van der Heyden (2002)</td>
</tr>
<tr>
<td>SN 1006</td>
<td>RGS Doppler O VII 4200 km s(^{-1}).</td>
<td>Vink (2003, 2009)</td>
</tr>
<tr>
<td>SNR 0509-67.5</td>
<td>Doppler 4900 km s(^{-1}).</td>
<td>Vink (2006); Kosenko (2008)</td>
</tr>
<tr>
<td>SNR 0519-69.0</td>
<td>4000 km s(^{-1}).</td>
<td>Kosenko (2010)</td>
</tr>
<tr>
<td>Tycho</td>
<td>Fe-K thermal &amp; (v_r = 4000) km s(^{-1}); prop.mo’ Si, S, Ar (v_r = 4700) km s(^{-1})</td>
<td>Katsuda (2010); Furuzawa (2009); Hwang (1')</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Hayto (2010 - Poster 8.03)</td>
</tr>
</tbody>
</table>

SNR 0519-69.0
w/RGS
Kosenko+ (2010)
Tycho (Type Ia)

- A. Hayto, Poster 8.03
- Layered structure effects velocities
  - \( v \) proportional to \( r \)
  - Si, S, Ar: velocity \( \sim 4700 \text{ km/s} \)
  - Fe: velocity \( \sim 4000 \text{ km/s} \)
  - Measurements w/CCDs!
- Side note:
  Type Ia's are "largely spherical" compared w/core-collapse (Lopez et al., 2009)
# Core-collapse SNR Results

<table>
<thead>
<tr>
<th>SNR Name</th>
<th>*</th>
<th>Measurement(s)</th>
<th>Reference(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cas A</td>
<td>[O]</td>
<td>$v_{Si} \sim 2000 \text{ km s}^{-1}$</td>
<td>Markert (1983); Holt (1994); Hwang (2001)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>. prop.mo'</td>
<td>Willingale (2002); Lazendic (2006); DeLaney (2)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Multi-$\lambda$: Ar, Si, Fe in 3D</td>
<td>DeLaney (2010)</td>
</tr>
<tr>
<td>E0102</td>
<td>[O]</td>
<td>$\sim \pm 1000 \text{ km s}^{-1}$</td>
<td>Flanagan (2004); Dewey (2002)</td>
</tr>
<tr>
<td>G292.0+1.8</td>
<td>[O]</td>
<td>Ne X $\sigma_v \sim 1500 \text{ km s}^{-1}$</td>
<td>Vink (2004), [aka MSH 11-54]</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Opt: bi-conical; $v_r \sim \pm 1500 \text{ km s}^{-1}$</td>
<td>Plunkett (2009); Winkler (2009)</td>
</tr>
<tr>
<td>N132D</td>
<td>[O]</td>
<td>$</td>
<td>v_{radial}</td>
</tr>
<tr>
<td>Puppis A</td>
<td>[O]</td>
<td>$v_{knot} \sim -1700, -3400 \text{ km s}^{-1}$</td>
<td>Katsuda (2008)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Opt: $v_r \sim -1600$ to $+1000 \text{ km s}^{-1}$</td>
<td>Garber (AAS 2010)</td>
</tr>
<tr>
<td>RCW 86</td>
<td></td>
<td>Fe-K 5000 $\text{ km s}^{-1}$ FWHM</td>
<td>Ueno (2007)</td>
</tr>
<tr>
<td>SN 1987A</td>
<td>?</td>
<td>$v_{\text{blast}} \sim 3400 \text{ km s}^{-1}$</td>
<td>Michael (2002)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$v_{\text{bulk}} \sim 200$–$500 \text{ km s}^{-1}$</td>
<td>Zhekov (2005); Dewey (2008)</td>
</tr>
<tr>
<td>SN 1996cr</td>
<td></td>
<td>$v_{\text{hydro}} \sim 4000 \text{ km s}^{-1}$</td>
<td>Bauer (2008); Dwarkadas (2010)</td>
</tr>
</tbody>
</table>

* Members of the O-rich class are indicated by [O].
SN 1996cr

- In Circinus Galaxy, distance 3.7 Mpc
- X-ray (and Radio) show increase at ~ 2+ years
- 500 ks HETG observation
- Model: Hydrodynamics + NEI X-ray emission
  - Single model, multi-epochs
  - CSM: wind-blown bubble
  - Dwarkadas et al. (2010)
SN 1996cr: Density profile

![Graph showing density profile](image)

- **Ejecta**
- **Free wind**
- **Shocked wind**
- **Swept-up Shell (RSG)**
- **RSG wind**

**Density (amu/cc)**

**Radius (pc)**

$t = 0.25$ yr.s
Model & Data Radii, Flux vs Time

5 mas

SN date = 1995.4

VLBI shell meas.
($r_{in} \rightarrow r_{out}$)
2007.5

shocked CSM
shocked Ejecta

D. Dewey       High-resolution X-Ray Spectroscopy: past, present & future       March 17, 2010
SN 1996cr: Multi-Epoch Spectra

velocity broadened data/model
Cas A - Multi-components in 3D

- DeLaney et al. (2010)
  - Paper published soon...
  - Combines Chandra (ACIS, HETG), Spitzer long-slit, and optical data.

Si XIII

[Ne II]

[Ar II]

[Si II]

optical knots

Fe-K
This figure to be available in the electronic edition of the Ap. J. as a 3D PDF file!
Cas A : "Ejecta pistons"

- Ejecta encounters reverse shock and emits in thin shell beyond reverse shock
- Whole columns ("pistons") are displaced outward
- There is _no_ spatial inversion of the layers
Toward the future

- X-ray kinematics are a key to understanding SN explosions
- Higher area enables SNe obs.s
  - "point sources" - grating is useful
- Cosmic Visions input:
  "3D SNR Reconstruction with IXO" (and Astro-H)
  - Many SNRs waiting to be observed
- Our 3D views of SNRs will be breathtaking!

thank you