A New Approach to X-ray Analysis of SNRs
The SPIES Project

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Supernova Remnants
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Crete, Greece
SNRs in (thermal) X-rays

- Shocked Plasma
  - Abundances
  - Kinematics
  - Temperatures
  - ...
  - => SN type, age, plasma conditions, CSM/ISM environment

- Difficult to characterize entire volume of SNR
  - Projection effects
  - Complex morphology
  - Many spectral components
  - Paucity of photons

Chandra ACIS (Frank+2015)
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Chandra ACIS (Yang+2008)
SPIES Project

Smoothed Particle Inference Exploration of SNRs

- MCMC procedure to fit the event file
  - Event positions and energies are not separated – truly spatially resolved spectroscopy

- Does not require unusually long exposure times

- Does not require strict assumptions on the spatial morphology

- Capability to model many spectral components along a line-of-sight and in the plane of the sky

- SPIES Project: Apply SPI to sample of 14 SNRs observed with XMM
  - Characterize full volume of SNR plasma
  - Variety of ages, types, and environments
Smoothed Particle Inference
Blob Spatial + Spectral Model → Generate Model Photons → Fold Through XMM Response → Compare Events → MCMC: Choose New Parameters and Repeat

$N_H, kT, n_eT, Mg, Si, S, Fe$

Observed Events

Model Events

SPI Fitting in Action
Data Products

- Set of spectral and spatial parameters for every blob for every iteration after convergence
  - Representative of the plasma conditions throughout the SNR

- Parameter Distributions

- Parameter Maps

- Can slice the data in any model dimension
  - e.g. map the abundances of the highest temperature plasma only
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RCW 103

Preliminary Results
RCW 103

Known Information

- Shell Morphology
- Distance $\sim 3.3$ kpc
- Age $\sim 2000$ years
- Diameter $\sim 9'$
- Core Collapse
  - Anomalous CCO
- X-ray Emission dominated by shocked CSM
- Frank+2015

XMM Observation

- MOS 1 and MOS 2
- Exposure $= 76$ ks
- $\sim 7.4 \times 10^6$ counts
- Si, S, Mg, Fe, Ne lines
  - not uniform across SNR
RCW 103

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**XMM Observation**

- MOS 1 and MOS 2
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Parameter Distributions

- **kT (keV)**
  - Values: 0.2, 0.4, 0.6, 0.8, 1.0, 1.2
- **Si (Si₆)**
  - Values: 0.2, 0.4, 0.6, 0.8, 1.0, 1.2
- **density (cm⁻³)**
  - Values: 1, 10, 100
- **nₑT (s cm⁻³)**
  - Values: 5e11, 1e12, 1.5e12, 2e12
Maps

Emission Measure (cm⁻³)
Plasma Components

Emission Measure (cm$^{-3}$)

Ionization Age (s cm$^{-3}$)

High kT
kT > 0.4 keV

Low kT
kT < 0.4 keV

Emission Measure (cm$^{-3}$)
Ionization Age (s cm$^{-3}$)

$n_e T$ (s cm$^{-3}$)

$n_e T$ (s cm$^{-3}$)
W49B
Preliminary Results
W49B

**Known Information**

- Elongated Central Bar
- Distance ~ 8 kpc
- Age ~ 1000-6000 years
- Diameter ~ 5'
- Core Collapse
  - No central object
  - Possibly jet-driven SN
- X-ray Emission dominated by shocked ejecta
- Miceli+2006, Lopez+2013(a), Lopez+2013(b)

**XMM Observation**

- MOS 1, MOS 2, and pn
- Exposure = 18.2 ks
- ~5×10^5 counts
- Si, S, Ar, Ca, Cr, Mn, Fe lines
  - not uniform across SNR

Chandra ACIS (Lopez+2013)
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Parameter Distributions

- **kT (keV)**
- **density (cm$^{-3}$)**
- **Fe (Fe$_{\odot}$)**
- **Ca (Ca$_{\odot}$)**
Emission Measure (cm$^{-3}$)
Plasma Components

Emission Measure (cm\(^{-3}\))  kT (keV)  Sulfur (S\(_\odot\))

High Density  n > 4 cm\(^{-3}\)

Low Density  n < 4 cm\(^{-3}\)
Abundance Ratios

Nucleosynthesis products from Nomoto+2006 (Isotropic) and Maeda+2003 (bipolar) models
Conclusions and What’s Next
Conclusions

- Smoothed Particle Inference
  - addresses many of the drawbacks of typical X-ray analysis methods
  - can characterize plasma in **full volume** of SNRs with typical X-ray exposure times
  - deeper investigation of **different plasma components**

![Diagram of data flow and events]
What’s Next

- RGS
- Non-thermal spectral components
- Expand to full 14 SNR sample
  - Ages
  - Types
  - Environments

<table>
<thead>
<tr>
<th>SNR Name</th>
<th>Angular Size (arcmin)</th>
<th>Type</th>
<th>D (kpc)</th>
<th>Radius (pc)</th>
<th>Age (yr)</th>
<th># EPIC counts</th>
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<tr>
<td>Cas A</td>
<td>5</td>
<td>CC</td>
<td>3.4</td>
<td>3.8</td>
<td>333</td>
<td>$5.2 \times 10^8$</td>
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<tr>
<td>W49B</td>
<td>4 x 3</td>
<td>CC</td>
<td>8.0</td>
<td>6.3</td>
<td>~ 1000</td>
<td>$4.6 \times 10^5$</td>
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<td>G11.2-0.3</td>
<td>4</td>
<td>CC</td>
<td>5.0</td>
<td>4.2</td>
<td>1628</td>
<td>$3.1 \times 10^5$</td>
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<tr>
<td>Kes 73</td>
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<td>CC</td>
<td>8.0</td>
<td>6.1</td>
<td></td>
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<td>G292.0+1.8</td>
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<td>CC</td>
<td>6.0</td>
<td>9.5</td>
<td>~ 3300</td>
<td>$4.9 \times 10^6$</td>
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<td>10</td>
<td>CC</td>
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<tr>
<td>3C 397</td>
<td>5 x 3</td>
<td>CC?</td>
<td>10</td>
<td>7</td>
<td>~ 5300</td>
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<td>CTB 109</td>
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<td>3</td>
<td>16</td>
<td>$1.4 \times 10^4$</td>
<td>$8.0 \times 10^5$</td>
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<td>Ia</td>
<td>5.0</td>
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<td>410</td>
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<tr>
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<td>Ia</td>
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<tr>
<td>N132D</td>
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<td>21.5</td>
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<tr>
<td>DEM L71</td>
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<td>11.9</td>
<td>~ 4360</td>
<td>$7.3 \times 10^5$</td>
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</tbody>
</table>
Bonus Slides
Convergence

RCW 103: $\frac{\chi^2}{\text{dof}} = 1.23$

W49B: $\frac{\chi^2}{\text{dof}} = 1.27$
Definition of $[X/Fe]$:

$$[X/Fe] = \log_{10}(N_X/N_{Fe}) - \log_{10}(N_X/N_{Fe})_{\odot}$$
Maps

Ca (Ca$_\odot$)
Maps

Ionization Age (s cm\(^{-3}\))