Recent Progress in Young Galactic* SNRs

Brian J. Williams (NASA GSFC / USRA)
@bjwilli2

*(plus some LMC stuff, too)*
I. Kinematics of SNRs

- More and more papers coming out on proper motions from SNRs

- As $t$ increases, this gets easier and easier to do in the era of high spatial resolution astronomy (JVLA, Hubble, ground-based optical, Chandra)

- But not just proper motions! Spectral information gives info on line-of-sight velocity as well…

- How does all of this translate into increased knowledge of SNRs and their progenitors?
Tycho’s SNR

Tycho
Tycho
Tycho’s SNR

Tycho’s SNR


Williams et al. 2013 measured densities of surrounding ISM, found evidence of density gradient
Reynoso et al. 1997, 10-yr baseline
Katsuda et al. 2010, 7-yr baseline
Plot from Williams et al. 2016, 15-yr baseline in X-rays, 30-yr in radio!
“But wait! Tycho is circular...”
Center, Ruiz-Lapuente et al. 2004
- Just because a remnant is circular, doesn’t mean the explosion site and geometric center are the same

- Effect is “only” ~10% for Tycho, but Tycho is dynamically young! Older remnants will show larger effects...

- See further talks on Tycho kinematics by Frank Winkler and Jack Hughes
Recent paper by Yamaguchi et al. 2016 derives proper motions for nonthermal (1800-3000 km/s) and thermal filaments (720 km/s)

- thermal velocities comparable to those reported by Helder et al. 2013 for optical Hα filaments

- consistent with predictions of Williams et al. 2011 that RCW 86 exploded in bubble, nonthermal rims are where shock hasn’t yet hit bubble wall; see D. Castro talk for physics of synchrotron emission
G1.9+0.3

Radio image, 1984

X-ray image, 2007
G1.9+0.3

Radio image, 1984

X-ray image, 2007

Reynolds et al. 2008
G1.9+0.3 is by far the youngest remnant in the Milky Way, age ~120 years (but no way it could have been seen from Earth at that time)
G1.9+0.3 is by far the youngest remnant in the Milky Way, age ~120 years (but no way it could have been seen from Earth at that time)

Lots of great science…

- Radio flux is still *brightening*, (Green et al. 2008)
- Overwhelmingly synchrotron-dominated, but spectral variations from place to place (Reynolds et al. 2009)
- Ejecta detected, asymmetrically-distributed, moving up to 18,000 km/s (Borkowski et al. 2009)
- Detected with NuSTAR up to 30 keV (Zoglauer et al. 2015)
- Expansion is asymmetric; see poster by S. Reynolds
Kepler's SNR

Figure 1(c) from Sankrit et al. 2015
- Shock velocities vary by a factor of 2

- Comparing proper motions to shock velocities derived from Hα spectroscopy, we get distance of 5.1 ± 0.8 kpc

- At this distance, mean shock velocity in north rim is 1690 km/s, pre-shock density ~8 cm⁻³
Chiotellis+ 2012 find Kepler is consistent with a symbiotic binary progenitor (i.e. single-degenerate) of WD + 4-5 $M_{\text{sun}}$ AGB star, favor large (> 6 kpc) distance.
Chiotellis+ 2012 find Kepler is consistent with a symbiotic binary progenitor (i.e. single-degenerate) of WD + 4-5 $M_{\text{sun}}$ AGB star, favor large (> 6 kpc) distance.

Tsebrenko & Soker 2015 use an “iron bullet” model to explain the “ears” in Kepler.
- Interacting with slow (10-20 km/s) wind, mass loss rate $> 4 \times 10^{-6} \, M_\odot \, yr^{-1}$

- Low-density cavity near SN prior to explosion

- Subenergetic explosions, large distances ($> 7 \, kpc$) required
Patnaude+ 2012

- Interacting with slow (10-20 km/s) wind, mass loss rate > 4 \times 10^{-6} \text{ M}_\odot \text{ yr}^{-1}
- Low-density cavity near SN prior to explosion
- Subenergetic explosions, large distances (> 7 kpc) required

- Burkey+ 2013 confirm that Kepler is most consistent with SD scenario

- Spatial morphology explained by dense equatorial wind
- North/south density gradient explained by system's movement in northward direction
Green spectrum from north rim

Yellow spectrum from south rim

Spectroscopic confirmation of much hotter dust in north than in south, density gradient required to produce this factor of 10-20 (Williams+ 2012)
Katsuda et al. 2015 find that Kepler is “An Overluminous Type Ia Event Interacting with a Massive Circumstellar Medium…,” a 91T-like SN
Katsuda et al. 2015 find that Kepler is “An Overluminous Type Ia Event Interacting with a Massive Circumstellar Medium…,” a 91T-like SN

Is there a link between Kepler and “Ia-CSM” SNe?
Bhalerao et al. 2015 used Chandra HETG spectra of several dozen knots to measure the red/blueshift of lines and get radial velocities.

- Ejecta knots vary from -2300 to +1400 km/s.

- Dynamics limit ejecta mass to $<8 \, M_\odot$ and progenitor mass to $<35 \, M_\odot$. 

**G292.0+1.8**
II. What can SNRs tell us about SN progenitors?

Stars

Supernovae

Supernova Remnants
II. What can SNRs tell us about SN progenitors?
II. What can SNRs tell us about SN progenitors?

Conceptually easy… but practically **impossible**!
One approach... reverse the problem

Solvable, though not easy
G284.3-1.8

See Williams et al. 2015

XMM-Newton image
It’s a binary! 16.6d period confirmed in X-rays and γ-rays.

Optical counterpart identified: 30 M☉ O6V((f)) star.

One of only two high-mass γ-ray binaries inside an SNR (SS 433 in W50).
Selected two bright regions for analysis: North & West
North region spectrum

Model:  
\textit{phabs x vpshock}

Abundances:
\begin{align*}
O & = 1 \\
\text{Ne} & = 1.19 \\
\text{Mg} & = 1.06 \\
\text{Si} & = 0.19 \\
\text{Fe} & = 0.24
\end{align*}

\[ kT = 0.67 \text{ keV} \]
\[ \tau = 4.6 \times 10^{12} \text{ cm}^{-3} \text{ s} \]

Chandra, XMM MOS 2
West region spectrum

Abundances:

\[ \text{O} \equiv 1 \]
\[ \text{Ne} = 1.30 \]
\[ \text{Mg} = 4.53 \]
\[ \text{Si} = 1.50 \]
\[ \text{Fe} = 0.97 \]

\[ kT = 0.92 \text{ keV} \]
\[ \tau = 1.0 \times 10^{11} \text{ cm}^{-3} \text{ s} \]

Chandra, XMM MOS 1, XMM MOS 2
West region rich in Mg, spectra and abundances similar to N49B in LMC (Park et al. 2003), another SNR with Mg-rich ejecta

Nucleosynthesis models produce significant amounts of Mg in explosions of massive (> 25 $M_\odot$) (Thielemann+ 1996)

SNR N49B
West region rich in Mg, spectra and abundances similar to N49B in LMC (Park et al. 2003), another SNR with Mg-rich ejecta.

Nucleosynthesis models produce significant amounts of Mg in explosions of massive (> 25 M☉) (Thielemann+ 1996).
West region rich in Mg, spectra and abundances similar to N49B in LMC (Park et al. 2003), another SNR with Mg-rich ejecta.

Nucleosynthesis models produce significant amounts of Mg in explosions of massive (> 25 $M_{\odot}$) (Thielemann+ 1996).

To reproduce observed properties, best fit binary evolution models have Star 2 with 27 $M_{\odot}$ initial mass.
3C 397

Yamaguchi et al. 2015

Spitzer (IR) & Suzaku (X-ray)
High Mn/Fe and Ni/Fe ratios imply high density in the WD core... which implies near Chandrasekhar mass WD... which implies single-degenerate progenitor
Katsuda et al. 2015 find that Kepler is “An Overluminous Type Ia Event Interacting with a Massive Circumstellar Medium…,” a 91T-like SN

Is there a link between Kepler and “Ia-CSM” SNe?
N103B (0509-68.7)

N103B appears to be second member of class of Type Ia SNRs with dense CSM, long after explosion (BJW+ 2014)
N103B (0509-68.7)

N103B appears to be *second* member of class of Type Ia SNRs with dense CSM, long after explosion (BJW+ 2014)

Stay tuned… approved for 400 ks with Chandra, plus 5 orbits HST

![Chandra Image](image1)

![Spitzer Image](image2)

![Graph](graph.png)