Asymmetric Expansion of the Youngest Galactic Supernova Remnant G1.9+0.3

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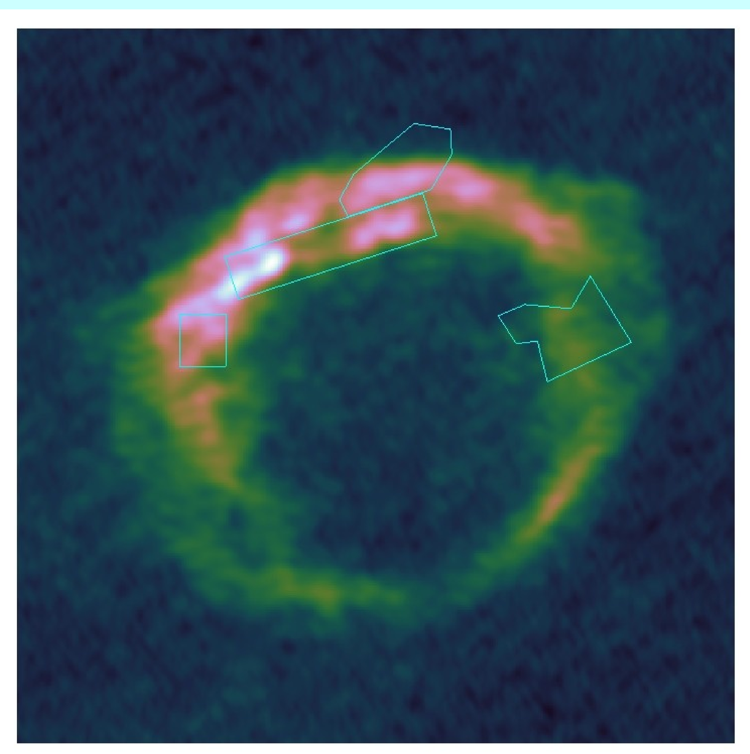
I. G1.9+0.3: The Youngest Galactic SNR

- Identified as youngest known Galactic SNR in 2008 (Reynolds et al. 2008; Green et al. 2008)
- Supernova explosion circa 1900 from global expansion measurements (Carlton et al. 2011; Borkowski et al. 2014)
- 2 pc in size at the Galactic Center distance of 8.5 kpc
- X-ray spectrum dominated by synchrotron emission; highly absorbed ($N_H \sim 6 \times 10^{22}$ cm^{-2})
- Most likely the result of an asymmetric Type Ia supernova explosion (Reynolds et al. 2008; Borkowski et al. 2013)

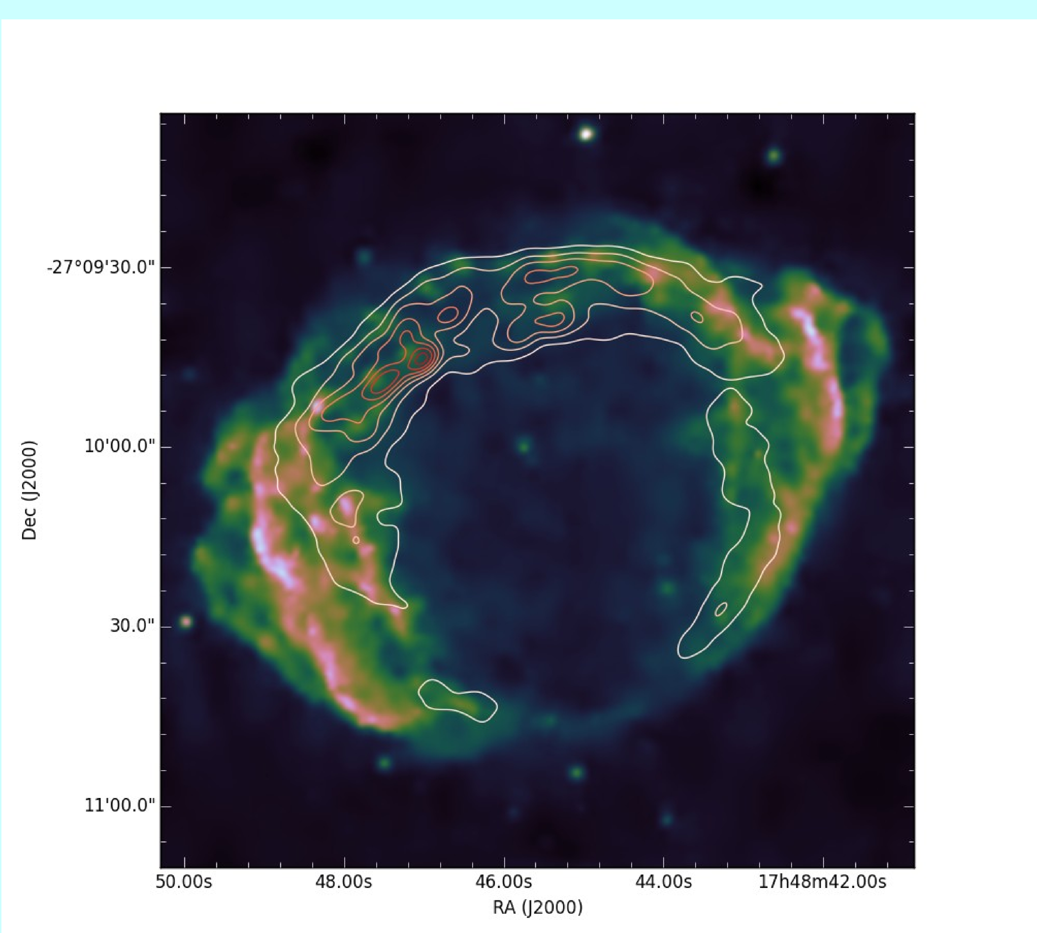
Up to 18,000 km/s free expansion velocities
No pulsar-wind nebula (but any neutron star/CCO would be hidden by high absorption)
Bilaterally symmetric X-ray synchrotron: like SN 1006

Asymmetric Radio Emission



1.4 GHz VLA image from 2008 December. The bright northern shell dominates, while prominent hard X-ray protrusions ("ears") in the NW and SE are very faint in radio. Bright radio emission correlates with ejecta emission detected by *Chandra* within overlaid regions (Borkowski et al. 2013). Intensities are shown with cubehelix color scheme of Green (2011).

X-ray – Radio Comparison



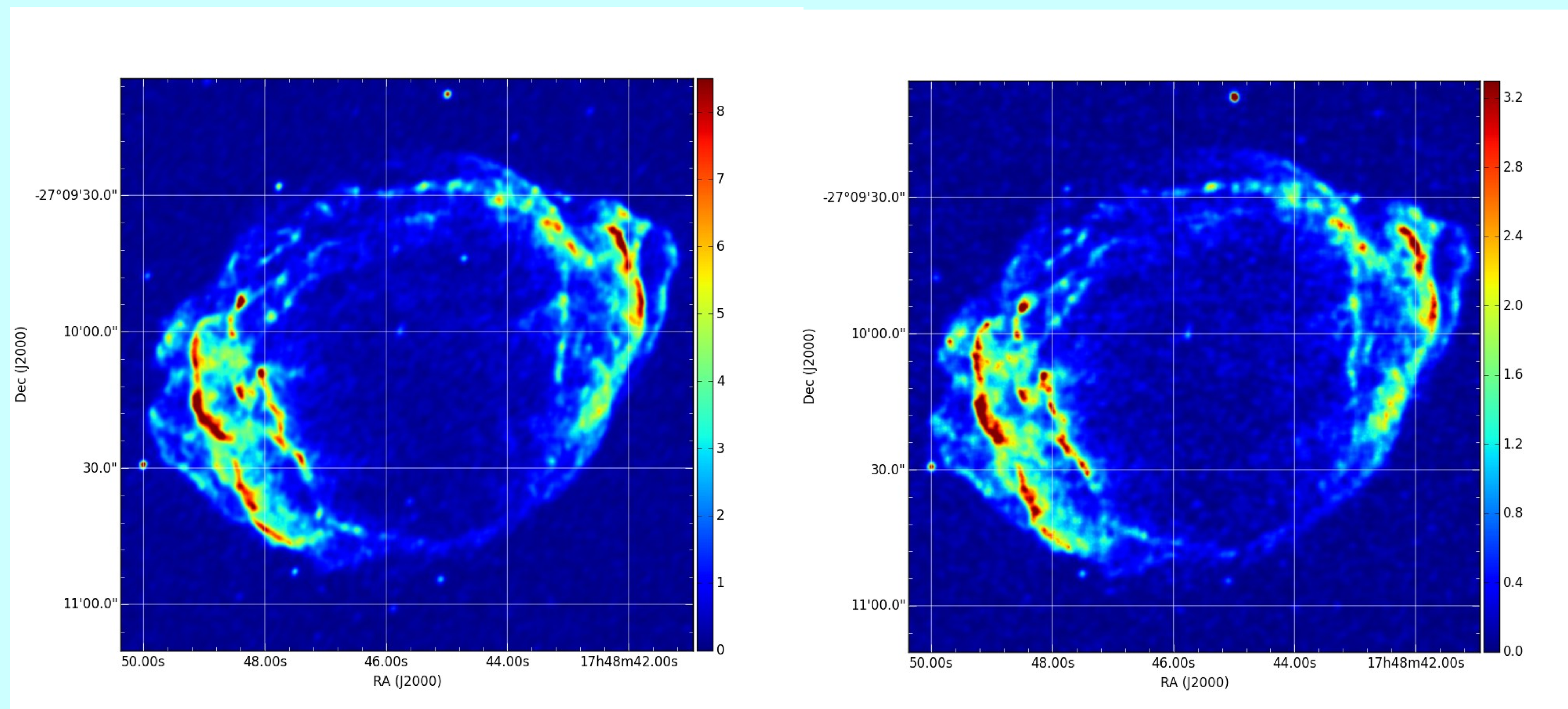
Chandra image from 2009, with overlaid radio contours showing bright radio emission. **We found relatively small X-ray proper motions along most of the outer edge of the bright radio emission in the north.** The peak radio brightness is displaced radially inward from an X-ray filament with the smallest measured proper motions.

II. Fourth Epoch Observations with *Chandra* in 2015

- Previous *Chandra* observations in 2007 (Epoch I; 50 ks), 2009 (Epoch II; 237 ks), and 2011 (Epoch III; 977 ks)
- Most recent (Epoch IV) *Chandra* observations took place in 2015 Spring and Summer (effective exposure time 392 ks), with the remnant again placed on the ACIS S3 chip
- 11 individual pointings from 2015 spatially aligned using photons from the remnant itself; observations from different epochs aligned to the deep Epoch III observation using point sources
- *Chandra* data cubes smoothed with the non-local PCA method of Salmon et al. (2014), with smoothed images extracted from these data cubes

Expansion from 2011 to 2015

2011 **2015**

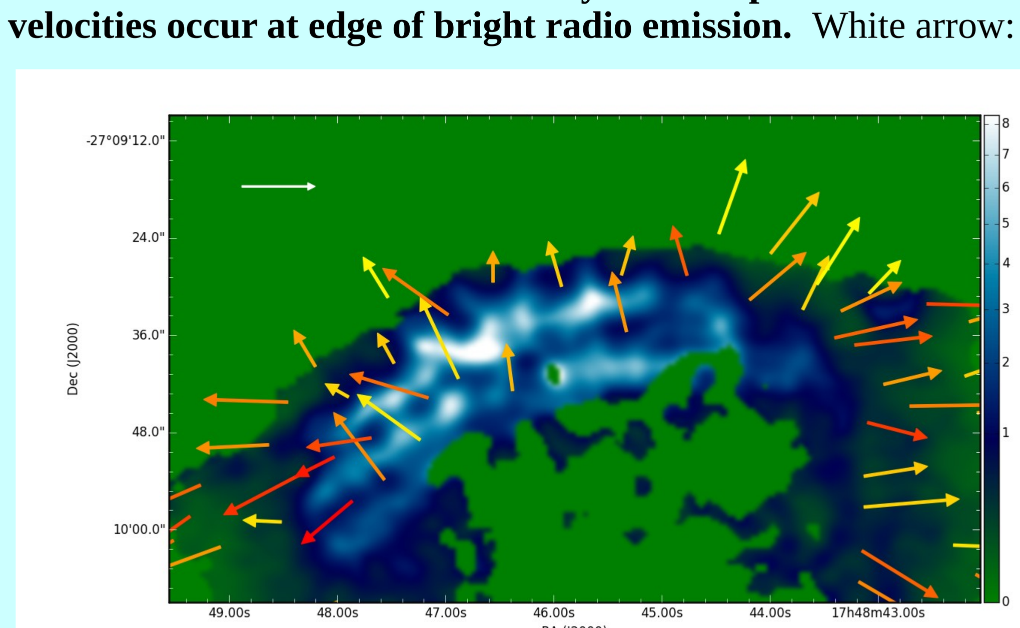


Smoothed X-ray images of G1.9+0.3 in the 1-8 keV energy range from 2011 (left) and 2015 (right), with a coordinate grid superposed. Expansion between these Epoch III and IV observations is apparent. During the 4.06 year baseline separating these epochs, we measure an **average expansion of 2.25%** (using the same method as in Carlton et al. 2011), but there are very large deviations from uniform expansion. Scale is in counts per 0.246" x 0.246" image pixel (half an ACIS pixel).

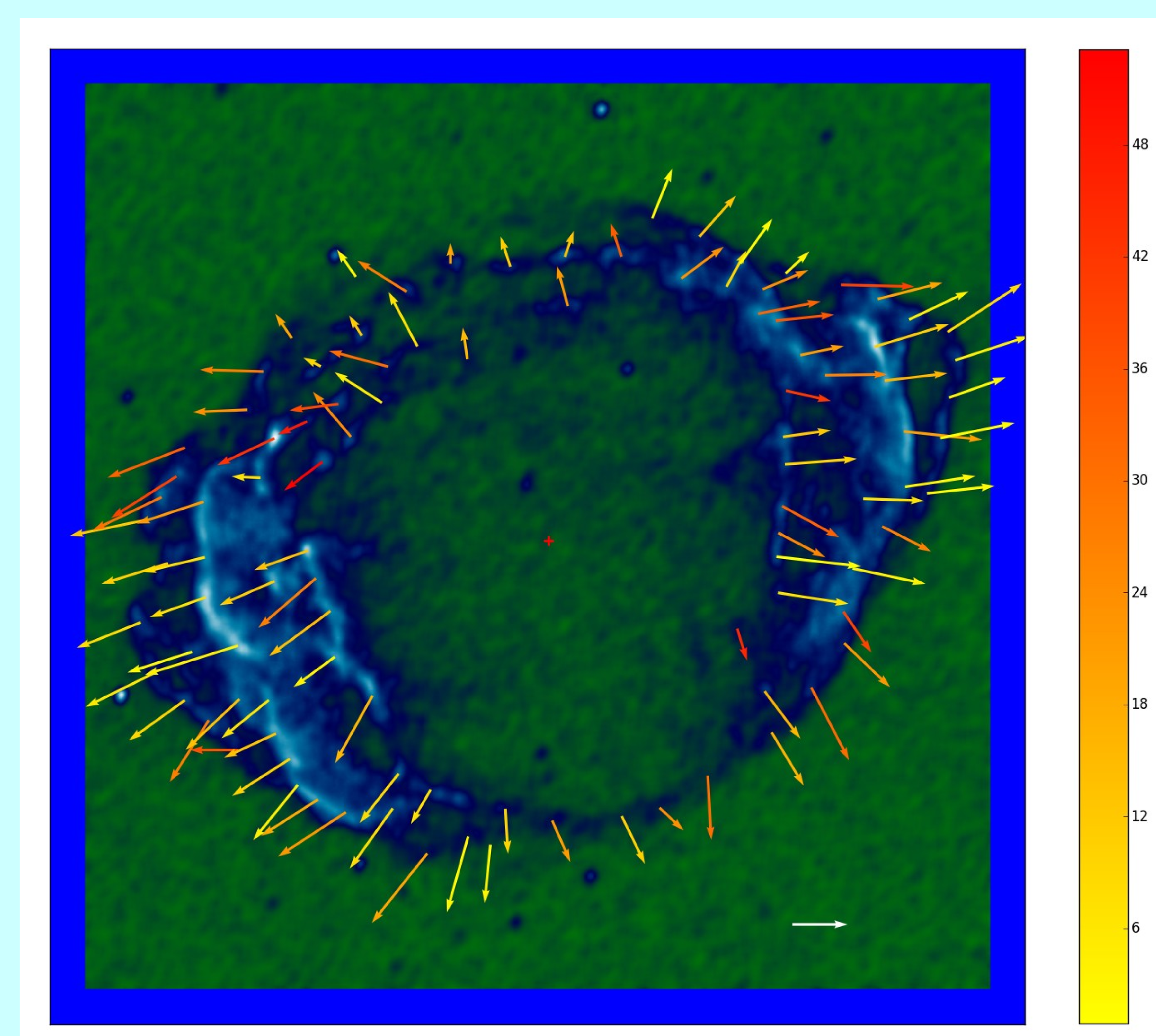
III. Proper Motion Measurements

Measurement Method

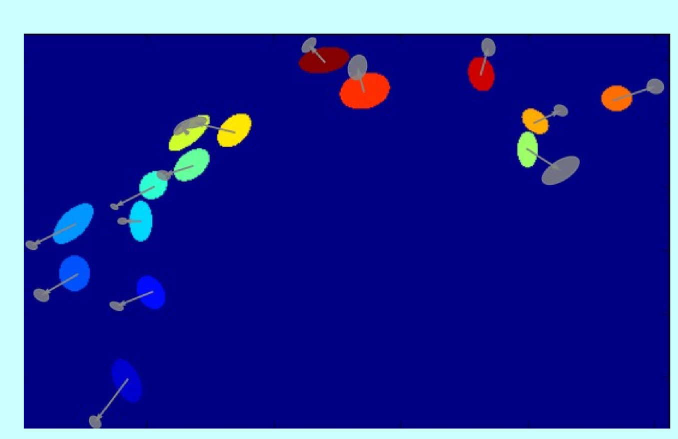
- Data are too complex for simpler methods as used in Carlton et al. (2011), Borkowski et al. (2014)
- Use "Demons" algorithm (Thirion 1998) in SimpleITK software package. Nonparametric method attributes image changes only to motions measured globally. Requires smoothed images.
- "Reference" image: 2011 1-8 keV smoothed image
- "Moving" image: 2015 1-8 keV smoothed image
- Mask out point sources, featureless interior
- Method finds displacement field mapping 2011 image into 2015 image
- Field smoothed by brightness-weighted averaging in small regions
- **Errors.** Use simpler parametric method to estimate.
- Use method of Carlton et al. (2011) allowing only displacements, not scale changes, for small regions
- Errors are non-isotropic; **conservative upper limits** since non-parametric method is global
- Example: one slow shock in NE has proper motion (0.09" ± 0.02")/yr
- Figure below right shows error ellipses (small grey ellipses) at ends of proper-motion vectors for some regions in N shell
- **Below: Vectors on 2009 radio/X-ray ratio map. Note smallest velocities occur at edge of bright radio emission.** White arrow: 0.25"/yr.



Results



Proper motion vectors in selected locations, color coded according to the deviations in direction from radial (with respect to the geometrical center of the remnant, marked by the red cross), in degrees according to the vertical scale. The white arrow indicates 0.25"/yr (10,100 km/s at 8.5 kpc). **Motions are between 0.09" and 0.44" per yr, varying by a factor of up to 5. The slowest shocks are in the north, at the outer boundary of the bright radio emission**, bracketed there by faster outer and inner shocks (the latter must be propagating into SN ejecta). The fastest motions are predominantly along the major axis of the remnant. Strongly nonradial motions suggest that the explosion occurred somewhere NE of the geometrical center. Extreme deviations from radial motions are present.



Error ellipses (at ends of vectors) for proper motions (obtained from parametric method)

IV. Conclusions

1. Expansion of G1.9+0.3 is highly asymmetric, varying in magnitude by a factor of 5 and strongly deviating from radial.

2. The measured proper motions, ranging from 0.09'' to 0.44'' per yr, correspond to shock speeds u(shock) between 3,600 km/s and 18,000 km/s (at 8.5 kpc). This offers us a unique opportunity to study how particle acceleration varies with shock speed. If maximum energies are limited by finite age, the spectrum rolls off at photon energy $h\nu_{roll} \propto u(\mathrm{shock})^4$, so the range in shock speeds we observe can explain the large range in observed rolloffs at different positions (Reynolds et al. 2009).

3. Shock velocities are slowest toward the north where radio emission is bright and thermal ejecta emission is most prominent. Such strong deceleration of the northern blast wave most likely arises from the collision of SN ejecta with much denser ambient medium there. The presence of the asymmetric ambient medium naturally explains the radio asymmetry.

4. The SN ejecta have also been strongly decelerated in the north, but they expand faster than the blast wave.

5. As with Kepler's SN - the most recent historical SN in the Galaxy - the SN ejecta are likely colliding with the asymmetric circumstellar medium (CSM) ejected by the SN progenitor prior to its explosion. G1.9+0.3 fills the gap between distant Type Ia-CSM SNe (e.g., Silverman et al. 2013) and older Type Ia-CSM SNRs such as Kepler's SNR (e.g., Burkey et al. 2013), providing us with a unique opportunity to learn about mysterious Type Ia progenitors.

References

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