Fast Expansion of Young, Ejecta-Dominated Supernova Remnant RCW 89 (MSH 15-52)

Kazimierz Borkowski, William Miltich, and Stephen Reynolds (North Carolina State University)

Young Core-Collapse Remnants of Stripped-Envelope Supernovae

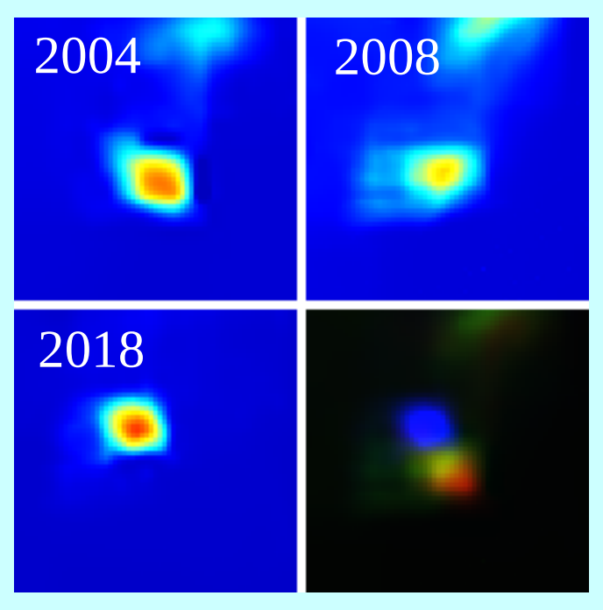
- Massive stars often lose most of their H (and even He) envelopes prior to their explosions, through processes that are still poorly understood. Explosions of such stripped stellar cores produce supernovae (SNe) Ibc and IIL/b.

- **Cas A**, the youngest known core-collapse (CC) supernova remnant (SNR) in our Galaxy, was produced by a SN IIb. It is very bright because SN ejecta are now colliding with the ejected stellar envelope. SN ejecta in Cas A are very fast and very clumpy.

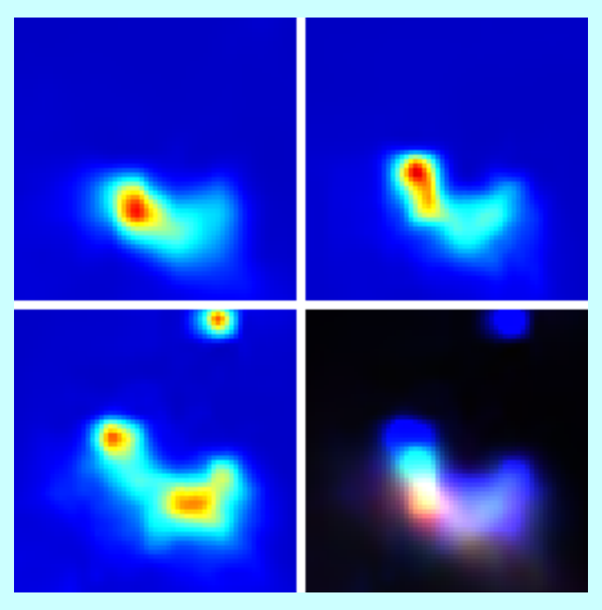
- Fast-moving and clumpy SN ejecta are likely to be signatures of young remnants of stripped-envelope SNe. Among young CC SNRs in our Galaxy, 1000-yr old **G330.2+1.0** (Borkowski et al. 2018), 1700-yr old **MSH 15-52 (RCW 89)** (Livingstone & Kaspi 2011), and 3000-yr old **G292.0+1.8** (Winkler et al. 2009) are distinguished by the presence of fast moving and clumpy SN ejecta.

- The relatively faint remnants G330.2+1.0 and MSH 15-52 were most likely produced by SNe Ibc, while the bright remnant G292.0+1.8 likely originated in a SN IIL/b explosion.

Ejecta Knot A

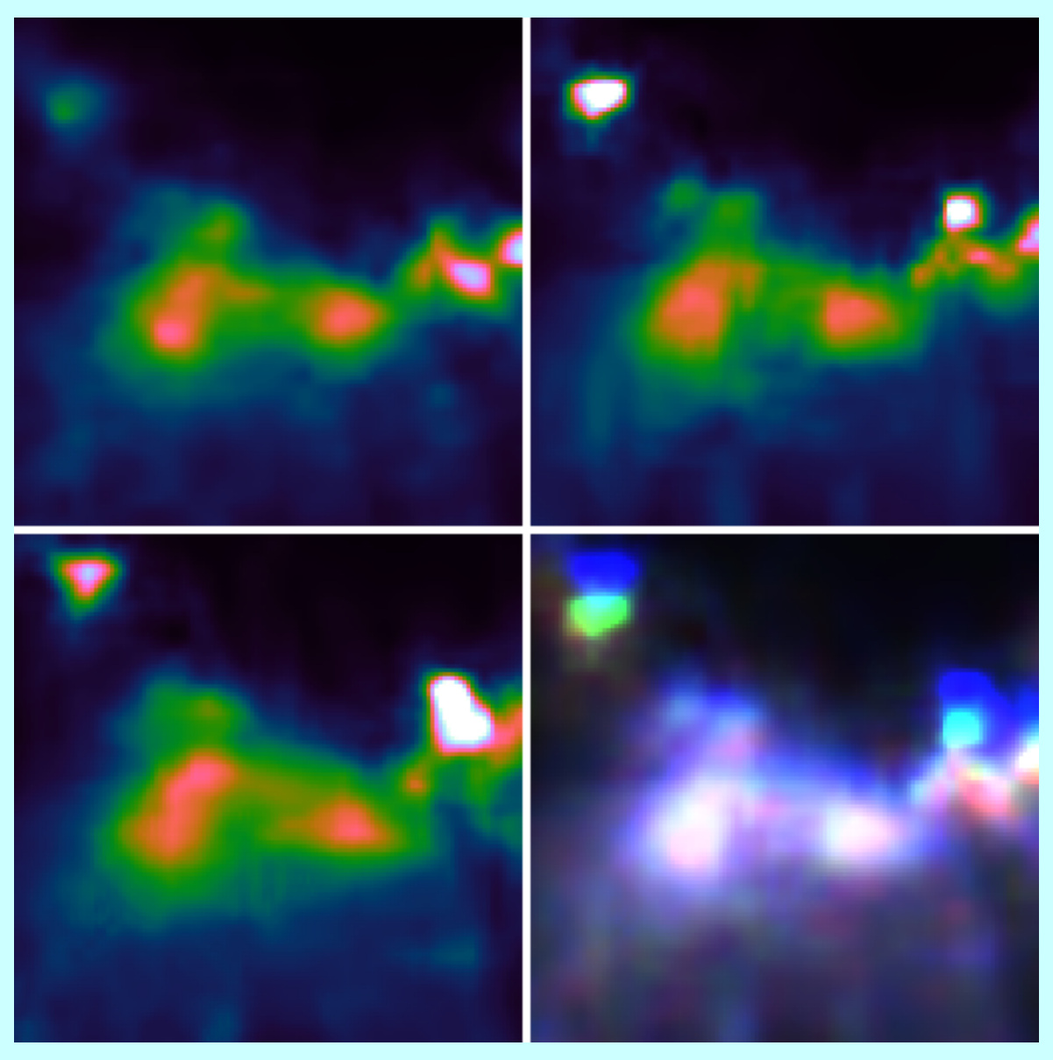


Ejecta Knot B



Ejecta knots A and B in 2004, 2008, and 2018. Their large motions are apparent. RGB images (bottom right at each panel) show them in more detail (red – 2004, green – 2008, blue -2018). **Bright ejecta knot NW of knot B is visible only in 2018.**

Slow Shock



X-ray- and radio-bright diffuse filament in the central part of RCW 89 in 2004, 2008, and 2018. The central part (excluding adjacent compact knots) moves radially away from the pulsar with speed of **(1380 +/- 120) $d_{5.2}$ km/s. This must be a strongly decelerated blast wave that has encountered a much denser than average ambient medium.**

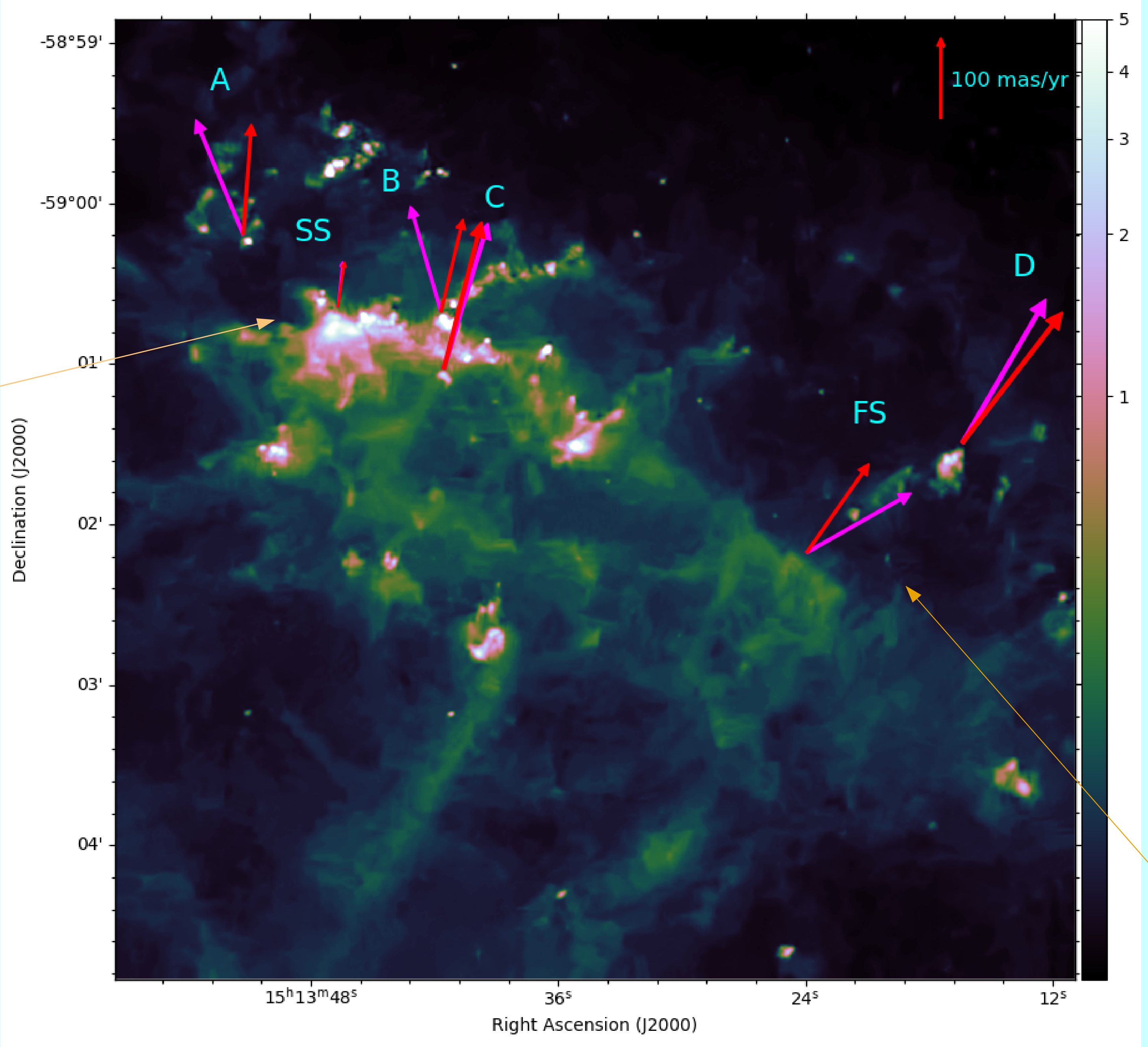
MSH 15-52 (RCW 89)

- Contains an energetic pulsar, PSR B1509-58, with 150 ms period, and an associated pulsar wind nebula (PWN).
- Pulsar's characteristic age is 1700 yr – remnant's age t should be less that this.
- Remnant's radius R is 19 $d_{5.2}$ pc ($d_{5.2}$ is distance in units of 5.2 kpc).
- Average shock speed R/t = 14,000 km/s (for t=1700 yr and 5.2 kpc distance determined by Gaensler et al. 2002).
- Very fast (4000 km/s on average) clumpy X-ray emitting SN ejecta were found in the north limb of MSH 15-52 (that is referred to as RCW 89) (Yatsu 2008).
- All available evidence is consistent with SN Ibc explosion (e.g., Chevalier 2005).

Chandra Observations of RCW 89

- Chandra observed RCW 89 in 2004 for 29 ks (Epoch I), in 2008 for 59 ks (Epoch II), and in 2018 for 185 ks (Epoch III).
- Epoch III observations were done in 5 pointings. We aligned them using emission from the remnant itself.
- Inter-epoch alignment was done using point sources. Our alignment errors are about 0.1 ACIS pixels, and lead to proper motion errors of about 5 mas per yr.

RCW 89 in 2018



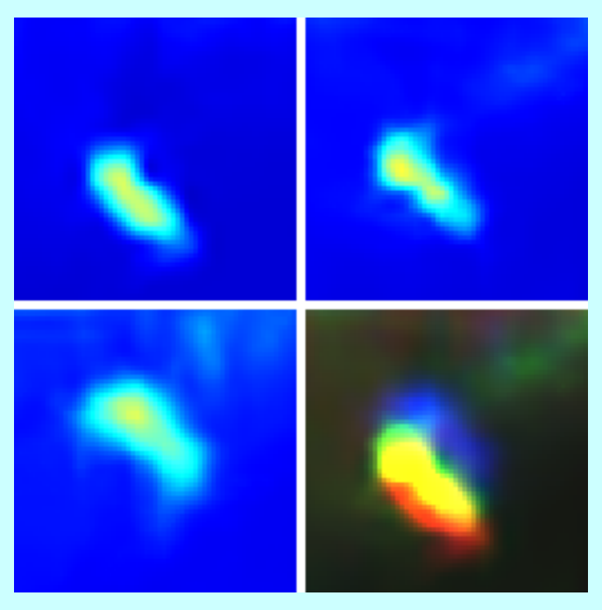
RCW 89 as seen by Chandra in 2018. Measured proper motions of selected features are shown by arrows (in magenta, not to scale; the scaling is shown by red arrow in the upper right corner of the image). Red arrows show the radial proper motion with respect to the pulsar. Proper motion of 100 mas/yr corresponds to 2470 $d_{5.2}$ km/s. Scale is in counts per 0.175"x0.175" image pixel.

PSR B1509-58, its PWN and RCW 89 as seen by Chandra in 2004/2005 (red: 0.5-1.7 keV, green: 1.7-3 keV, blue: 3-8 keV). Image is 19.6' across. Credit: NASA/CXC/SAO/P.Slane et al.

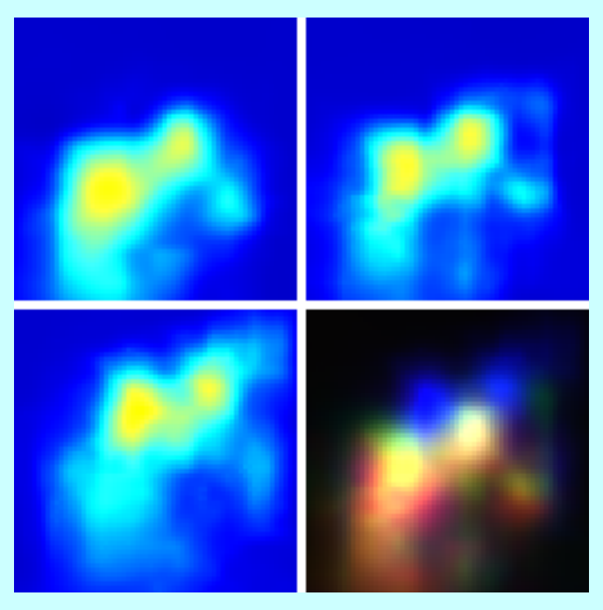
Expansion Measurements

- Motions of ejecta knots and shocks were modeled as simple image shifts.
- Measurements were done using smoothed and unsmoothed image pairs on Epoch I – III and Epoch II – III time baselines.
- Poisson statistic was assumed for unsmoothed images. Maximum likelihood method was employed (Cash 1979).
- Images were smoothed using method of Azzari & Foi (2016).

Ejecta Knot C



Ejecta Knot D



Ejecta knots C and D in 2004, 2008, and 2018. Their large motions are apparent. RGB images (bottom right at each panel) show them in more detail (red – 2004, green – 2008, blue -2018). Knot C moves radially away from the pulsar with speed of **(4660 +/- 130) $d_{5.2}$ km/s**, while the radial motion of knot D is **(5060 +/- 120) $d_{5.2}$ km/s**. **Among Galactic CC SNRs, such high speeds are found only in Cas A and G330.2+1.0.** But these ejecta knots have already suffered a significant deceleration as their deceleration parameters are 0.73 for knot C and 0.71 for knot D (in these estimates, we assumed that the explosion site is coincident with the current pulsar location.)

Fast Shock

This is a fast moving shock with purely nonthermal X-ray synchrotron spectrum. Based on the 2008 and 2018 data, we find the radial velocity of **(3300 +/- 300) $d_{5.2}$ km/s**, while the tangential component is **(1600 +/- 500) $d_{5.2}$ km/s** (errors might be somewhat underestimated). This is the long-sought fast **primary blast wave** of MSH 15-52 that has not been yet detected at radio wavelengths (Leung 2018).

Conclusions

1. Very fast (up to 5000 km/s) SN ejecta are present in RCW 89, with several compact knots moving radially away from the centrally-located pulsar although nonradial motions can also be found. But even the fastest moving ejecta have been strongly decelerated, as the deceleration parameter m ($R \propto t^m$) is less than ¾. X-ray spectra are dominated by Ne and Mg, so these ejecta knots are products of hydrostatic burning.

2. Morphologies of most ejecta knots have changed between the three observing epochs, and several knots have brightened or faded by up to a factor of several. Entirely new ejecta knots appeared in 2018. This variability is likely caused by the rapid deceleration of SN ejecta as they suddenly encounter a much denser than average ambient medium north and northwest of the pulsar.

3. The blast wave has been strongly decelerated in some locations, with velocities as low as 1400 km/s where the radio surface brightness is the highest. These are regions with particularly high ambient medium densities.

4. A much faster (3300 km/s) primary blast wave was found in RCW 89. There are no lines in its spectrum, so we are seeing purely nonthermal X-ray synchrotron radiation produced by shock-accelerated TeV electrons.

5. It will be interesting to compare in detail the ejecta dynamics seen in Cas A, RCW 89, and G292.0+1.8. In G292.0+1.8, we found nearly undecelerated outlying ejecta knots, with the deceleration parameter of 0.95. This is somewhat unexpected since RCW 89 is significantly younger than G292.0+1.8.

6. Synchrotron X-ray temporal variations have already been found in the 1000-yr old SNR G330.2+1.0. This young remnant of a SN Ibc might be as dynamic and variable as RCW 89.

References

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