

The Expansion Rate of a Supernova Remnant – partial answer key

There is no full answer key for this investigation. The idea of this exercise is to introduce students to the methods used by scientists to study the expansion of supernova remnants. Students will not have access to all the statistical tools used by scientists and making sure the same spot on a region is being measured from one observation to the next can be tricky. Students are also just looking at a small sample of data.

Estimating the expansion velocity of the forward shock in Cas A:

Here is a screenshot of some sample data taken in this activity with js9 (for images 10 years apart) and the calculations to find the expansion velocity of the forward shock. The region numbers correspond to those in the image and table underneath by [Delaney and Rudnick, 2002](#) which used images 2 years apart.

| | | | | | | | |
|------------------------|------------------------|--------------------------------|-------------|-----------|----------------|-------------------|--|
| expansion center (RA) | 350.868853 | dist. from Earth to Cas A (km) | 1.05E+17 | | | | |
| expansion center (dec) | 58.81372222 | time betw. obs. (s) | 316065078 | | | | |
| FORWARD SHOCK | | | | | js9 calculated | vel. From | |
| region # | distance of region | distance of region | expansion | expansion | expansion | DeLaney & Rudnick | |
| | from neutron star 2004 | from neutron star 2014 | of region | of region | velocity | w/2 yr spread | |
| | (arc sec) | (arc sec) | (radians) | (km) | (km/s) | | |
| 2 | 151.024801 | 155.895569 | 2.36142E-05 | 2.48E+12 | 7837 | 6520 | |
| 14 | 148.072804 | 150.483595 | 1.16879E-05 | 1.23E+12 | 3879 | 4511 | |
| 4 | 131.341116 | 134.73961 | 1.64764E-05 | 1.73E+12 | 5468 | 5497 | |
| 29 | 166.276767 | 170.163573 | 1.88438E-05 | 1.98E+12 | 6254 | 6190 | |
| 7 | 162.343744 | 165.735595 | 1.64442E-05 | 1.72E+12 | 5458 | 4956 | |
| 28 | 167.755643 | 171.642368 | 1.88434E-05 | 1.98E+12 | 6254 | 6028 | |
| 8 | 150.040802 | 151.959593 | 9.30257E-06 | 9.76E+11 | 3087 | 4961 | |
| 22 | 135.284356 | 138.675631 | 1.64414E-05 | 1.72E+12 | 5457 | 5764 | |
| 20 | 140.200836 | 141.135604 | 4.53189E-06 | 4.75E+11 | 1504 | 2504 | |
| 3 | 135.772816 | 138.675582 | 1.4073E-05 | 1.48E+12 | 4671 | 4361 | |
| | | | | | | | |
| | | | | | | | |
| | | | | | | | |
| mean velocity | 0 | 172.177711 | 0.000834742 | 8.76E+13 | 4987 | 4916 | |

Table 2. Forward Shock Fragment Measurements

| Region | Azimuth (degrees) | Radius (arcsec) | Expansion Rate (% yr ⁻¹) | Expansion Rate Error (% yr ⁻¹) | Radius ^a (pc) | Velocity ^a (km s ⁻¹) | Velocity Error ^a (km s ⁻¹) |
|---------------|-------------------|-----------------|--------------------------------------|--|--------------------------|---|---|
| 1 | 51.8 | 167.83 | 0.196 | 0.024 | 2.77 | 5296 | 647 |
| 2 | 38.8 | 147.59 | 0.274 | 0.010 | 2.43 | 6520 | 245 |
| 3 | 42.0 | 132.75 | 0.204 | 0.036 | 2.19 | 4361 | 763 |
| 4 | 41.1 | 126.42 | 0.270 | 0.025 | 2.08 | 5497 | 505 |
| 5 | 37.0 | 134.91 | 0.261 | 0.025 | 2.22 | 5668 | 537 |
| 6 | 20.8 | 156.34 | 0.259 | 0.037 | 2.58 | 6519 | 930 |
| 7 | 12.2 | 158.80 | 0.194 | 0.018 | 2.62 | 4956 | 465 |
| 8 | 1.8 | 147.42 | 0.209 | 0.011 | 2.43 | 4961 | 250 |
| 9 | 353.0 | 156.65 | 0.099 | 0.022 | 2.58 | 2498 | 561 |
| 10 | 347.3 | 157.17 | 0.186 | 0.039 | 2.59 | 4723 | 996 |
| 11 | 347.0 | 153.00 | 0.159 | 0.056 | 2.52 | 3929 | 1376 |
| 12 | 348.1 | 145.80 | 0.167 | 0.050 | 2.40 | 3934 | 1179 |
| 13 | 341.2 | 157.45 | 0.249 | 0.041 | 2.60 | 6308 | 1030 |
| 14 | 338.4 | 151.01 | 0.185 | 0.010 | 2.49 | 4511 | 232 |
| 15 | 234.3 | 160.77 | 0.321 | 0.053 | 2.65 | 8324 | 1377 |
| 16 | 208.2 | 134.96 | 0.021 | 0.016 | 2.22 | 452 | 353 |
| 17 | 192.3 | 157.12 | 0.107 | 0.022 | 2.59 | 2722 | 542 |
| 18 | 188.9 | 152.39 | 0.197 | 0.060 | 2.51 | 4841 | 1461 |
| 19 | 186.7 | 147.30 | 0.215 | 0.016 | 2.43 | 5106 | 382 |
| 20 | 191.4 | 136.53 | 0.114 | 0.020 | 2.25 | 2504 | 435 |
| 21 | 180.4 | 132.84 | 0.197 | 0.045 | 2.19 | 4225 | 970 |
| 22 | 175.7 | 132.22 | 0.270 | 0.035 | 2.18 | 5764 | 741 |
| 23 | 154.2 | 150.29 | 0.111 | 0.042 | 2.48 | 2691 | 1005 |
| 24 | 152.5 | 145.90 | 0.275 | 0.041 | 2.40 | 6459 | 964 |
| 25 | 144.7 | 142.93 | 0.218 | 0.030 | 2.36 | 5029 | 686 |
| 26 | 136.9 | 154.85 | 0.246 | 0.019 | 2.55 | 6137 | 462 |
| 27 | 125.0 | 157.73 | 0.252 | 0.021 | 2.60 | 6404 | 529 |
| 28 | 122.8 | 165.01 | 0.227 | 0.027 | 2.72 | 6028 | 729 |
| 29 | 108.5 | 162.07 | 0.237 | 0.016 | 2.67 | 6190 | 412 |
| mean | | 149.18 | 0.204 | | 2.46 | 4916 | |
| median | | 151.01 | 0.209 | | 2.49 | 5029 | |
| rms | | 11.03 | 0.066 | | 0.18 | 1623 | |
| error in mean | | 2.05 | 0.012 | | 0.03 | 301 | |

^aAssuming distance of 3.4 kpc

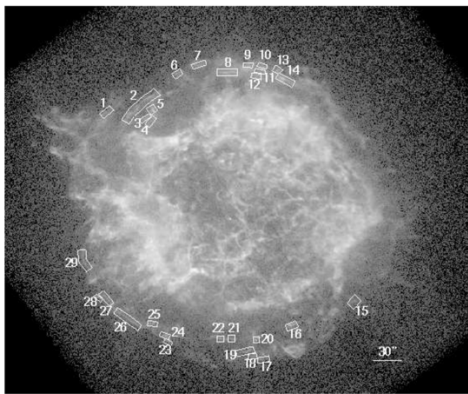


Fig. 1.— The second epoch *Chandra* X-ray image of Cas A (log brightness scale) with measured proper motion regions marked.

Estimating the age of Cas A from knots in the jet:

Again, here is a screenshot of some sample data taken in this activity with js9. Please note that these knots are in x-rays whereas the following data from Fesen et al, 2006 examines optical knots.

| JETS | distance of region from neutron star 2004 (arc sec) | distance of region from neutron star 2014 (arc sec) | expansion of region (radians) | expansion of region (km) | js9 calculated expansion velocity (km/s) | |
|---------------|---|---|-------------------------------------|--------------------------------|---|------------|
| | 233.074421 | 242.479035 | 4.55949E-05 | 4.78E+12 | 15133 | |
| | 204.390139 | 208.522523 | 2.00344E-05 | 2.10E+12 | 6649 | |
| | 214.6213 | 219.346496 | 2.29084E-05 | 2.40E+12 | 7603 | |
| | 197.994149 | 204.094541 | 2.95756E-05 | 3.10E+12 | 9816 | |
| | | | | MEAN | 9800 | |
| CONCLUSION #3 | diameter (arc sec) | radius (rad) | radius (km) | velocity km | time (s) | time (y) |
| | 300 | 0.00072722 | 7.63E+13 | 9800 | 7784220517 | 246.804709 |
| | | | | | DATE | 1757.19529 |

From [Fesen et al, 2006](#)

“When the proper motion extrapolations are replaced with predicted knot proper motions based solely on March 2004 knot positions and the COE [center of expansion], a structure of opposing jet features and north and south gaps appears even more striking (Fig. 2, bottom panel). The circle in the figure marks a radial distance of 200'' from the COE corresponding to a proper motion of 0.''625 yr⁻¹ for an age of 320 years and an implied $\approx 10,000$ km s⁻¹ transverse velocity assuming a remnant distance of 3.4 kpc.”

“Age Estimates Assuming No Knot Deceleration : The average arrival date for the 1825 outer knots with undecelerated extrapolated arrival dates between 1580 and 1750 is 1662 \pm 27 yr. This is consistent with that estimated by Thorstensen et al. (2001) who found an undecelerated convergent date of 1671.3 \pm 0.9 based on a sample of 17 especially long-lasting knots for which archival imaging data were available covering a time span of up to 50 years.”

12

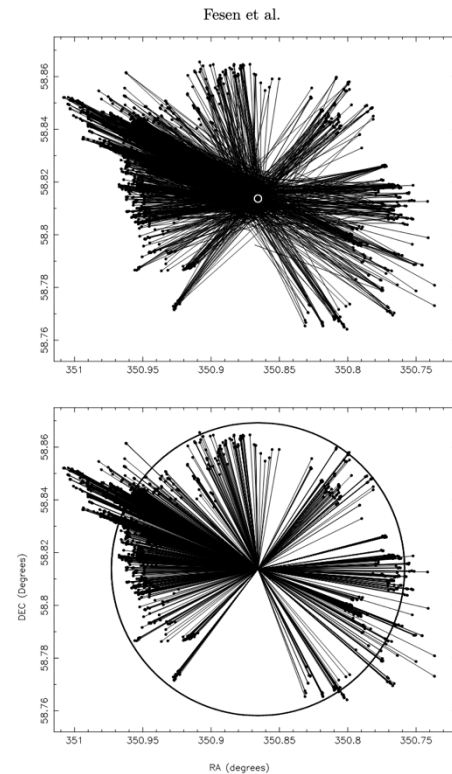


FIG. 2.— Top: Plot of extrapolated 320 yr proper motions for the 1825 identified outer knots based on actual proper motions measured using the March and December 2004 ACS/WFC data. Central white circle has a radius of 5'' and marks the remnant's estimated center of expansion (Thorstensen et al 2000). Bottom: Plot of 1825 outer knot positions and their expected motions away from the remnant's known center of expansion revealing a 'bow-tie' asymmetric structure. Circle represents the radial distance of 200'' corresponding to a measured proper motion of 0.''625 yr⁻¹ and thus an implied 10,000 km s⁻¹ transverse velocity at the assumed remnant distance of 3.4 kpc.