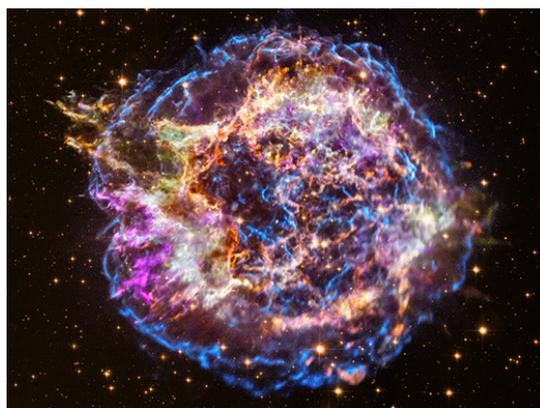


The Expansion Rate of a Supernova Remnant – a js9 activity

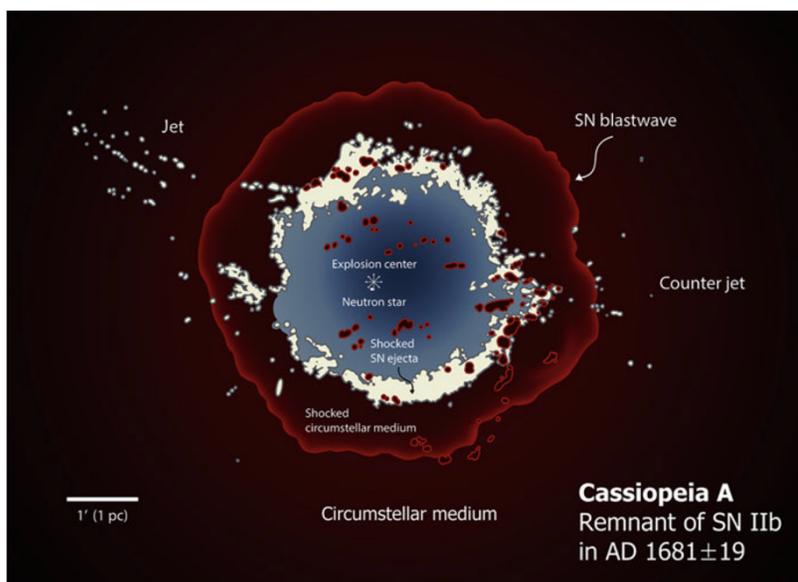
Purpose: To analyze observational data of a supernova remnant to determine the expansion velocity.

Every 50 years or so, a massive star in our galaxy blows itself apart in a supernova explosion. Supernovas are one of the most violent events in the universe, and the force of the explosion generates a blinding flash of radiation, as well as shock waves analogous to sonic booms. In this activity, we will be studying Cassiopeia A, a well-known supernova remnant located about 11,000 light years from Earth. Cas A is a type II SNR produced by the catastrophic collapse of the core of a massive star.

In the composite X-ray/optical image to the right, the blue, outer region of Cas A shows the expanding blast wave of the explosion. This forward shock is composed of shock waves similar to the sonic booms generated by a supersonic aircraft. An inner shock wave is believed to be due to the collision of the ejecta from the supernova explosion with a circumstellar shell of material (CSM), heating it to a temperature of ten million degrees. The bright object near the center may be the neutron star that remained after the explosion that produced Cas A. Watch a movie [here](#).



Cassiopeia A in X-ray and optical light.



The expansion rate of the remnant has been used to estimate how long ago the explosion occurred, but is the expansion rate constant and do all parts of the remnant expand at the same rate? Let's examine the data from two observations of the Chandra X-Ray Observatory taken about ten years apart with the same observational parameters.

Features of Cas A, white and blue represent SN material, red the CSM, Koo and Park, 2017

Procedure:

Finding the average velocity of the forward shock

1. Go to <https://chandra.si.edu/js9/>.
2. In the js9 window on the left, go to **File>close>this image**.
3. Click "The Unofficial Chandra Archive Search Page" button and type "5320" in the ObsID box and click "Search." Click the 5320 link under "ObsID" in the results.
4. Drag the link "acisf05320N004_cnr_img2.fits.gz" to the js9 window and then **Zoom>zoom 1/2**.

Index of /cdaftp/byobsid/0/5320/primary

- [acisf05320N004_cnr_img2.fits.gz](#)
- [acisf05320N004_cnr_img2.jpg](#)
- [acisf05320N004_evt2.fits.gz](#)
- [acisf05320N004_full_img2.fits.gz](#)
- [acisf05320N004_full_img2.jpg](#)
- [acisf05320_000N004_bpix1.fits.gz](#)
- [acisf05320_000N004_fov1.fits.gz](#)
- [orbitf200059500N001_eph1.fits.gz](#)
- [pcadf05320_000N001_asol1.fits.gz](#)
- [responses/](#)

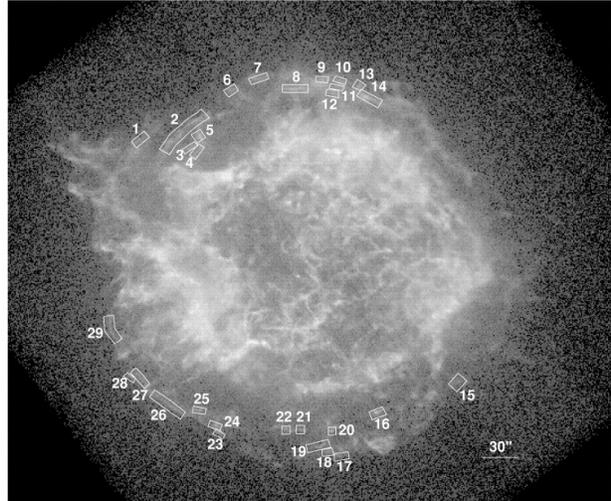
5. Repeat steps #1-4 to load the 2014 observation with ObsID 14481. Go to **File>separate>separate these images** to put them side by side.
6. The expansion center of Cas A was determined by a previous study to be RA = 23h23m27s, Dec = 58°48'49" (Thorstensen et al 2001). Convert right ascension and declination to degrees in decimals as follows. Record this in the data section.

RA: (hours + minutes/60 + seconds/3600) X 15

Dec: degrees + minutes/60 + seconds/3600

7. In the window on the left, go to **Regions>circle**. Click on the green region to select it. Go to **Regions>selected region**. Next to "edit" enter your RA and Dec from step 6 and then click "apply" and close the window. Repeat this on the other window.

8. The size of the regions can be changed by moving your cursor over a corner until it changes to an arrow and then dragging. Change the size of the region (keeping it on the center of expansion) so that it is approximately tangent to a segment of the forward or outer shockwave. Make sure the cursor is an arrow and not a cross or you will end up moving the region. If you move the region by accident, reset its position as shown in step #7. Examples of such segments are shown in the image to the right from another observation. Do this for both ObsID 5320 and ObsID 14481. Go to **Regions>list** and record the radius of the region which is the last number in parentheses in arcsec (“) for each image. Subtract these radii to get the expansion distance of this shockwave segment. Repeat for a total of 10 segments or more. If you wish, you can go to **File>Print** and mark and number your own sections on the image. See the **Addendum** for suggestions on highlighting features of Cas A to help with this analysis. For this particular step, try **Color>grey** and **Scale>Log**.



DeLaney and Rudnick, 2002

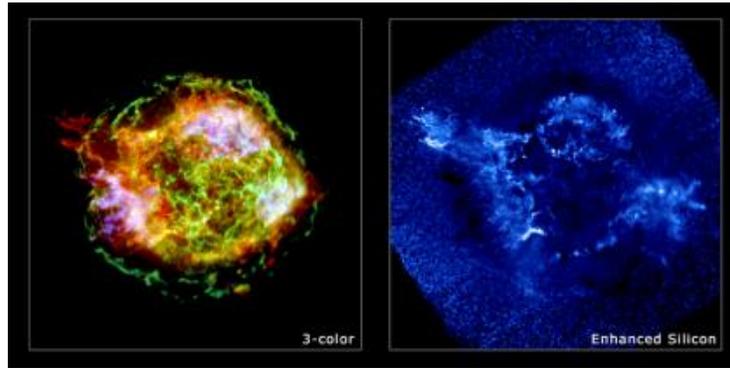
9. Convert the distance from Earth to Cas A from light years (see the **Data/Analysis section** below) to kilometers where $1 \text{ ly} = 9.461 \times 10^{12} \text{ km}$.
10. Convert the expansion distances from arcsec to km using the small angle formula.

$$d = (\theta_{\text{arcsec}}) \times D / 206265$$

where D = distance to Cas A in km, θ = expansion in arcsec

11. Find the time in seconds between the start dates for the two observations (see **data**) using <https://www.timeanddate.com/date/timeduration.html>.
12. Find the expansion velocity of each segment ($v = d/t$) using the distances from step 10 and the time between observations from step 11 and then average them.

Finding the average velocity of jets



Credit: NASA/CXC/GSFC/U.Hwang et al.

13. In the image above, you can see a large jet beyond the forward shockwave in the upper left and, in the enhanced silicon image, a counter jet in the lower right. Repeat the process for finding the average velocity of the forward shock to that of regions in the jets.

Data/Analysis:

Note: If you are familiar with spreadsheets, set one up to do the repeated calculations. The radii from step #9 can be highlighted, copied and pasted into the spreadsheet.

ObsID	RA	Dec	Exposure time (ks)	Start date
5230	23h 23m 26.70s	+58°49'03"	54.0	5/5/2004 time 22:59:36
14481	23h 23m 26.70s	+58°49'03"	50.0	5/12/2014 time 02:50:54

Expansion center: RA = 23h 23m 27s = _____ deg in decimals
 Dec = 58°48'49" = _____ deg in decimals

D (distance to Cas A) = 11090 light years = _____ km

Time between observations = _____ days _____ hours _____ seconds = _____ s

Forward Shock

Section #	Radius of region ObsID 5320 (arcsec)	Radius of region ObsID 14481 (arcsec)	Expansion of forward shock segment (arcsec)	Expansion of forward shock segment (km)	Expansion Velocity (km/s)
Ave. or mean velocity of forward shock (km/s)					

Jets

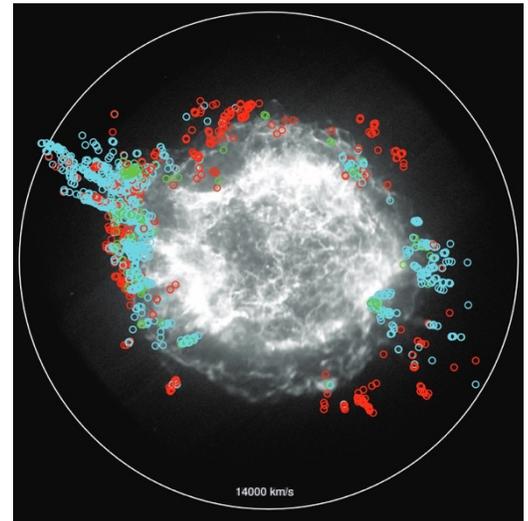
Section #	Radius of region ObsID 5320 (arcsec)	Radius of region ObsID 14481 (arcsec)	Expansion of forward shock segment (arcsec)	Expansion of forward shock segment (km)	Expansion Velocity (km/s)
Ave. or mean velocity of ejecta (km/s)					

Conclusions:

1. How does the mean or average velocity of the forward shock compare to that of the jet?
2. Discuss experimental error in your values. Remember also that you are looking at a two dimensional image of a three dimensional object. (Check out some cool 3D animations of Cas A [here](#).)

The proper motion of the SN material could give an estimate as to its age, however, the forward shock has experienced significant deceleration due to the interaction with the ambient medium. To the right is an image showing fast moving knots (FMKs) in Hubble Space Telescope images. Red, green and blue open circles indicate knots with strong [N II], [O II], and [S II] line emissions, respectively. These FMKs are denser and have experienced little deceleration.

3. Go back to your 2014 observation in js9. Use a region centered on the expansion center to measure the diameter of Cas A. Using the small angle formula, the radius of Cas A and your mean velocity results, determine a method for finding the age of Cas A. Explain your method and show your calculations. What assumptions are you making?



Fesen et al., 2006

Extensions:

From Koo and Park, 2017:

Two possible historical records of the Cas A supernova:

A record from Korean astronomers reports that a guest star appeared at the first star in the west of Wangyang on December 4, 1592. In the next three months, the location of the guest star was consistently described as ‘inside the first star in the west of Wangyang.’ The westmost star in the constellation of Wangyang is β Cassiopeia (β Cas). The angular distance between β Cas and the expansion center of Cas A is 5.9° .

In 1680 (Gregorian calendar), John Flamsteed, the first Astronomer Royal of England, catalogued a nonexistent 6th magnitude star in the constellation Casseopeia. This star is about 10 arcmin off Cas A and has never been observed again.

1. There are some interesting conjectures as to whether or not the supernova explosion of Cas A was observed. Do some research. What can you find? What are accepted values for the date of this explosion?

From [The Latest Look at "First Light" from Chandra](#)

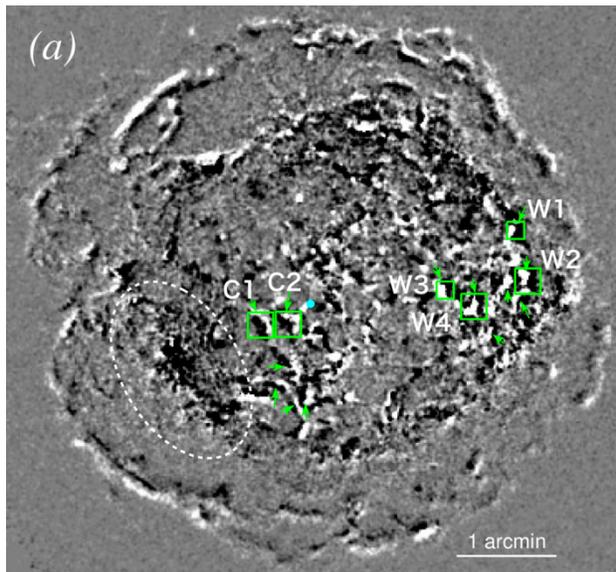


Image difference in the 4.2–6 keV band of Cas A between 2000 and 2014, Sato et al 2017

“As the (forward) blast wave travels outwards at speeds of about 11 million miles per hour, it encounters surrounding material and slows down, generating a second shock wave - called a "reverse shock" - that travels backwards, similar to how a traffic jam travels backwards from the scene of an accident on a highway.

These reverse shocks are usually observed to be faint and much slower moving than the blast wave. However, a team of astronomers led by Toshiki Sato from RIKEN in Saitama, Japan, and NASA’s Goddard Space Flight Center, have reported reverse shocks in Cas A that appear bright and fast moving.”

2. The image above shows areas of reverse shock (green boxes) studied by Sato et al, 2017. Use the techniques learned in this activity to study the reverse shock yourself. Record your data and findings.

ADDENDUM: Suggestions to highlight features of Cas A to help with this analysis.

1. Try various colormaps under **Color**. Also try **Color>Invert**.
2. **Contrast** refers to the rate of change of color with color level. Contrast is adjusted by dragging the left mouse button or two fingers on a touch screen vertically in the display window. Try this and watch the color bar.
3. **Bias** refers to any offset added to the color levels before the color map is applied. In other words, it determines where the color changes start. Bias is adjusted by dragging the left mouse button or two fingers on a touch screen horizontally in the display window. Try this and watch the color bar.
4. Go to **Color>reset contrast/bias**. Notice that you can also change contrast and bias here by entering numbers.
5. Try different scales (**Scale>linear**, **Scale>log** etc).
6. In either window, go to **WCS>wcs reproject** and choose the other image to line them up if necessary.

References:

- Delaney, Tracey, and Lawrence Rudnick. "The First Measurement of Cassiopeia A's Forward Shock Expansion Rate." *The Astrophysical Journal*, vol. 589: 819–826, 1 June 2003.
- Fesen, Robert A. "The Expansion Asymmetry and Age of the Cassiopeia A Supernova Remnant." *The Astrophysical Journal*, 645: 283–292, 1 July 2006.
- Gotthelf, E. V., et al. "Chandra Detection of the Forward and Reverse Shocks in Cassiopeia A." *The Astrophysical Journal*, 552:L39–L43, 1 May 2001.
- Koo, Bon-Chul, and Changbom Park. "Supernova Remnant Cassiopeia A ." *Handbook of Supernovae*, by Athem W. Alsabti and Paul Murdin, Springer., Cham, 2017, p. 161.
- "Photo Album: Cassiopeia A: Cassiopeia A Animations." Harvard-Smithsonian Center for Astrophysics, www.chandra.harvard.edu/photo/2009/casa2/animations.html.
- Sato, Toshiki et al. "X-Ray Measurements of the Particle Acceleration Properties at Inward Shocks in Cassiopeia A." *The Astrophysical Journal*, 6 Dec. 2017
- Thorstensen, John R, and Robert A Fesen. "The Expansion Center and Dynamical Age of the Galactic Supernova Remnant Cassiopeia A." *The Astronomical Journal*, 122:297–307, July 2001.
- "The Latest Look at 'First Light' from Chandra." *Chandra X-Ray Observatory - NASA's Flagship X-Ray Telescope*, Harvard-Smithsonian Center for Astrophysics, chandra.si.edu/photo/2019/firstlight/index.html.

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 from center 2004 (arc sec)	distance of region from center 2014 (arc sec)	expansion of region (arc sec)	expansion of region (km)	expansion velocity (km/s)	DeLaney & Rudnick w/2 yr spread	
2	151.024801	155.895569	4.870768	2.48E+12	7837	6520	
14	148.072804	150.483595	2.410791	1.23E+12	3879	4511	
4	131.341116	134.73961	3.398494	1.73E+12	5468	5497	
29	166.276767	170.163573	3.886806	1.98E+12	6254	6190	
7	162.343744	165.735595	3.391851	1.72E+12	5458	4956	
28	167.755643	171.642368	3.886725	1.98E+12	6254	6028	
8	150.040802	151.959593	1.918791	9.76E+11	3087	4961	
22	135.284356	138.675631	3.391275	1.72E+12	5457	5764	
20	140.200836	141.135604	0.934768	4.75E+11	1504	2504	
3	135.772816	138.675582	2.902766	1.48E+12	4671	4361	
mean velocity					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	

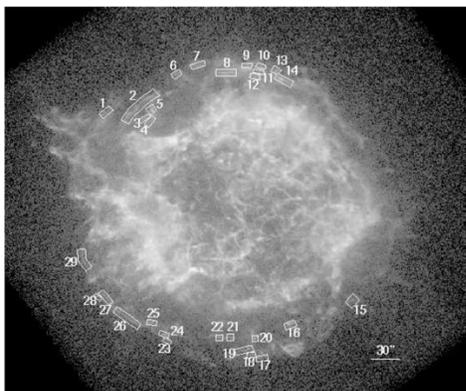


Fig. 1.— The second epoch *Chandra* X-ray image of Cas A (log brightness scale) with measured proper motion regions marked.

^aAssuming distance of 3.4 kpc

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 (arc sec)	expansion of region (km)	js9 calculated expansion velocity (km/s)	
	233.074421	242.479035	9.404614	4.78E+12	15133	
	204.390139	208.522523	4.132384	2.10E+12	6649	
	214.6213	219.346496	4.725196	2.40E+12	7603	
	197.994149	204.094541	6.100392	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 ≈ 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±27 yr. This is consistent with that estimated by Thorstensen et al. (2001) who found an undecelerated convergent date of 1671.3±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

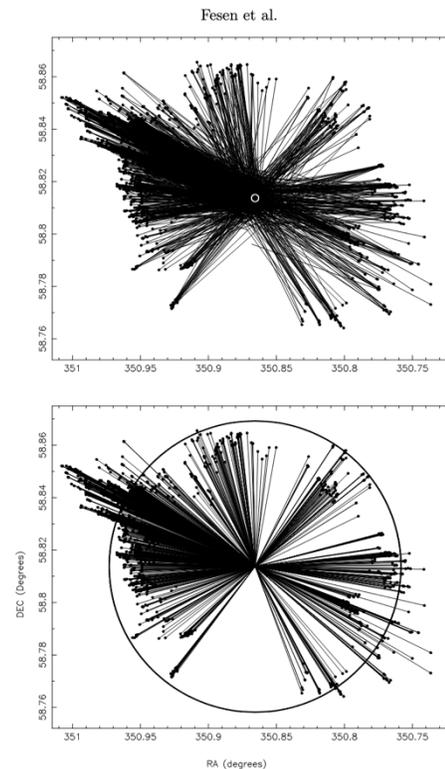


FIG. 2.— *Top*: Plot of extrapolated 320 yr proper motions for the 1825 identified outer knots based on actual proper motions measured using the March and December 2004 ACS/WFC data. Central white circle has a radius of 5'' and marks the remnant's estimated center of expansion ([Thorstensen et al 2001](#)). *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.''65 yr⁻¹ and thus an implied 10,000 km s⁻¹ transverse velocity at the assumed remnant distance of 3.4 kpc.