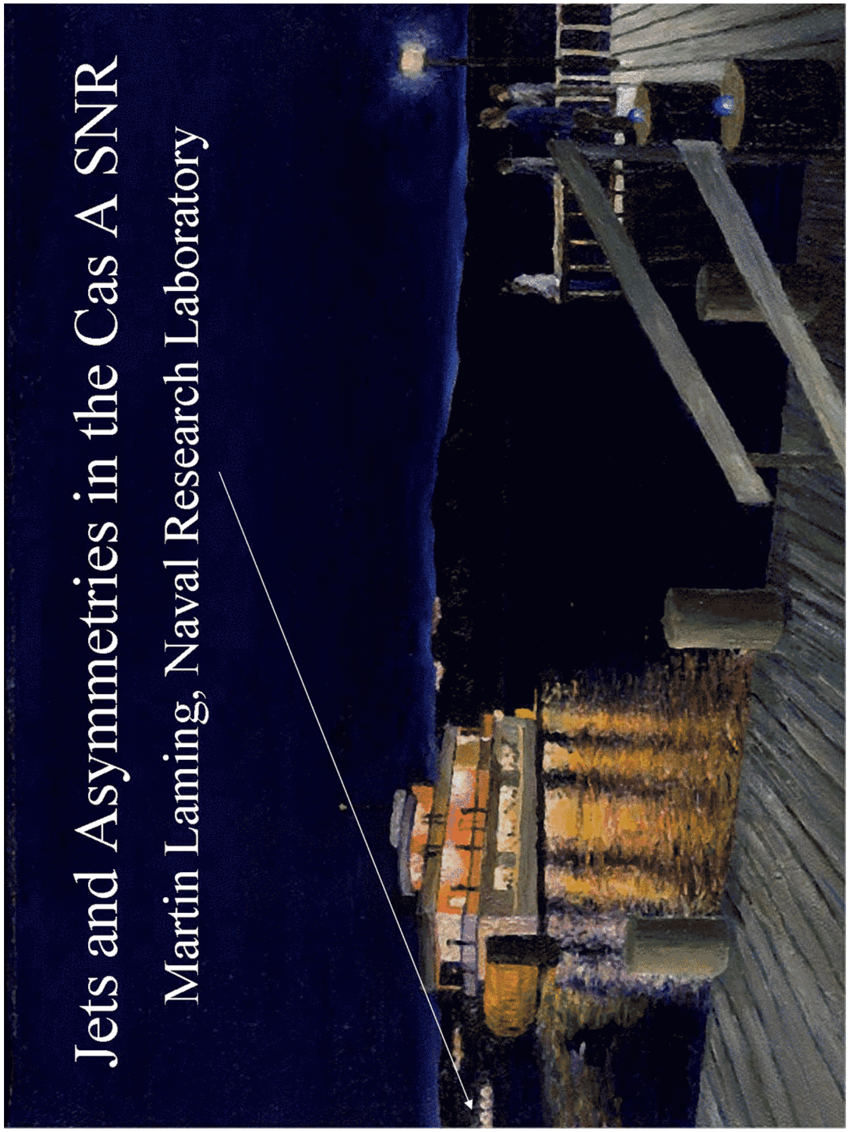
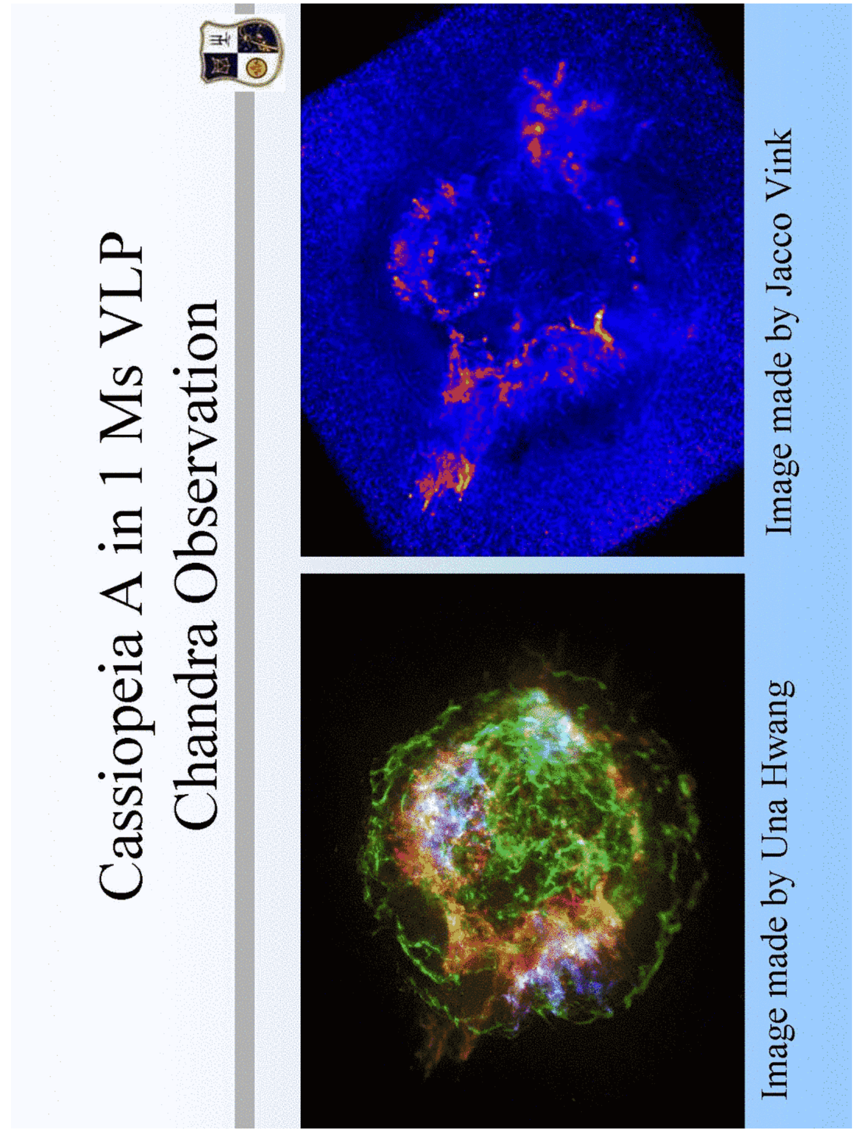
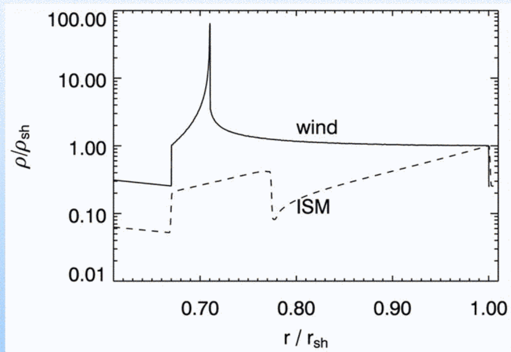

Jets and Asymmetries in the Cas A SNR
Martin Laming, Naval Research Laboratory


Cassiopeia A in 1 Ms VLP
Chandra Observation
Image made by Jacco Vink
Image made by Una Hwang

Cassiopeia A Vital Statistics

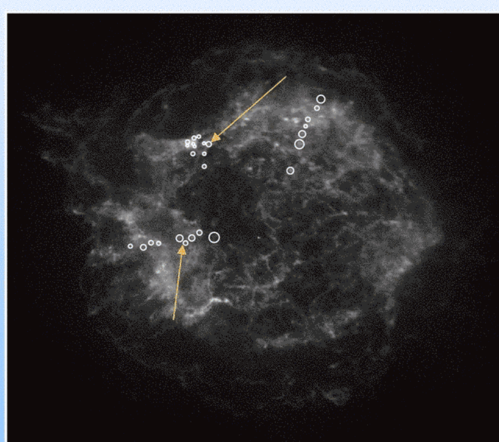


Models from Chevalier & Oishi (2003), ApJ, 593, L23

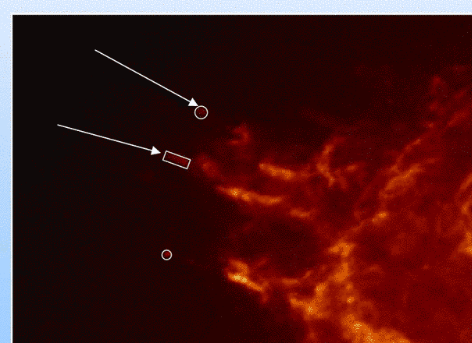
- Youngest galactic (core collapse) SNR.
- Well studied at all energies (except the EUV).
- D = 3.4 kpc, explosion ~1660-1670 AD, forward shock speed 5000-6000 km/s, radius = 2.5 pc.
- Ratio forward/reverse shock radii = 1.5 – 1.8 (i.e. varies).
- ~2 $M_\odot$ ejecta dominate X-ray emission in Cas A, often appear in knots.
- 20-25 $M_\odot$ progenitor, down to ~4 $M_\odot$ upon explosion due to stellar wind mass loss (see Patrick Young – Friday).

Isolate emission from ejecta "knots", measure T_e and n_et

50 ksec Chandra

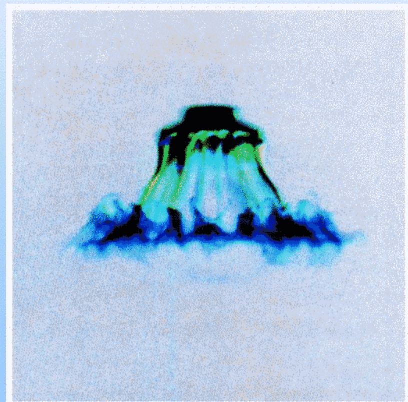


1 Msec Chandra



Rationale: Shock-Knot Interactions

from Klein et al. 2003, ApJ, 583, 245 (@ $3t_{cc}$).



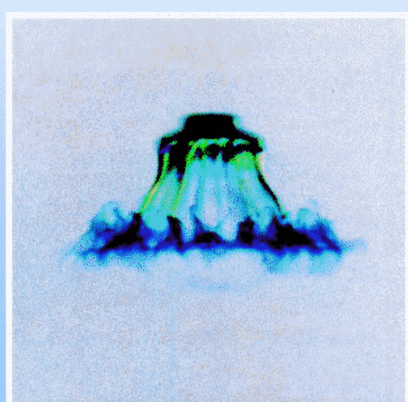
Size scale of knots is: 1" ~ 0.02 pc
At velocity 2000 km/s, time for reverse shock to cross a knot is:
10 yr << 320 yr (age of remnant).

Significantly overdense knots will not survive hydro instabilities to be seen ~300 years later!

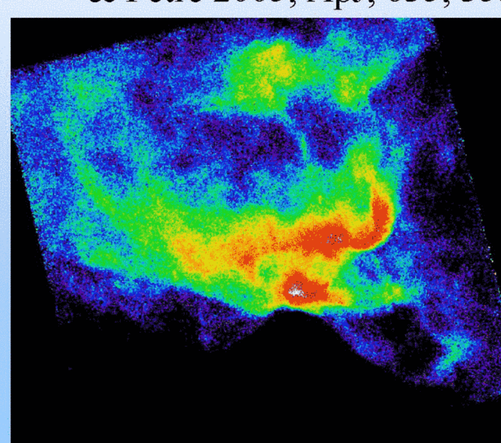
Fit single ionization ages to knot spectra. We also fit single temperatures.

Rationale: Shock-Knot Interactions

from Klein et al. 2003, ApJ, 583, 245 (@ $3t_{cc}$).



Puppis A, from Hwang, Flanagan & Petre 2005, ApJ, 635, 355



Survival of Knots

Instabilities will shred knots over a few knot crossing times (~50 yrs, comparable to the lifetime of optical knots) if the knot is significantly overdense (or underdense).

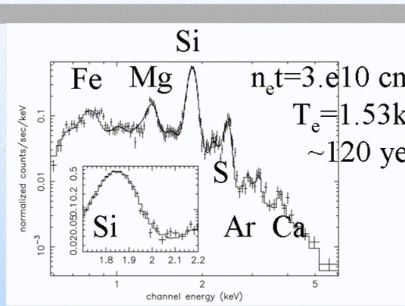
Knots can survive the lifetime of Cas A as knots if they were not more than a few times more dense than their surroundings.

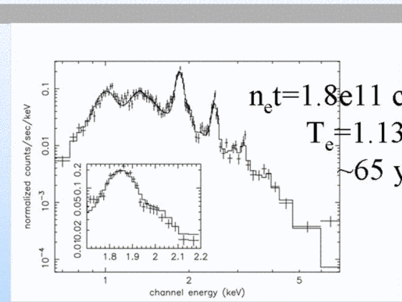
We believe knots appear as such because of their composition: heavier metals have higher emissivities via line emission.

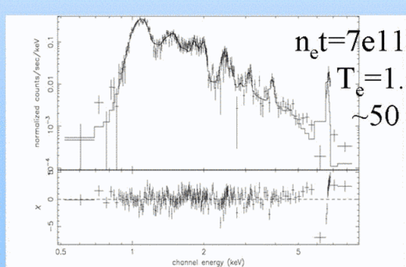
X-ray knots are not the same as the optical knots, which are known to be dense.

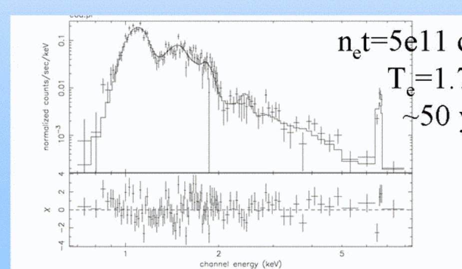
"Knot" spectra (from 50 ks obs.)

notice how Si XIII/XIV and Fe L spectrum change with n_et

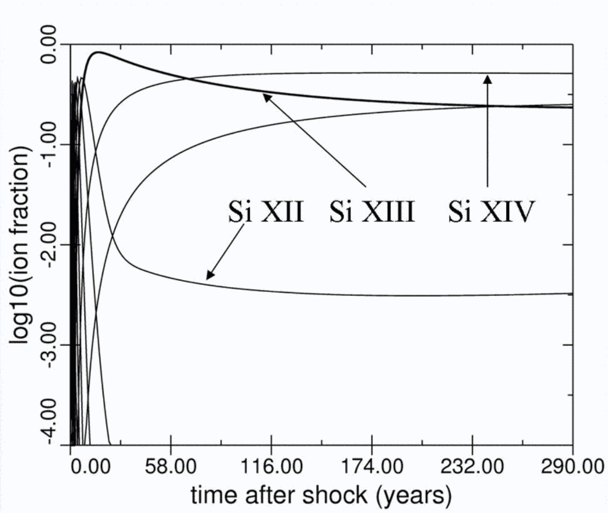








Si charge states behind reverse shock



Example of reverse shock passage 50 years after explosion.

He-like Si is dominant for ~60 years postshock.

With a hydrodynamic model we can infer mass coordinates for the ejecta clumps, using $n_e t$ and T_e from fits.

Hydrodynamic Models

Analytical approximations of Truelove & McKee (1995) extended for circumstellar wind medium, density ~ $1/r^2$.
Ejecta with uniform density core/power law envelope, $\rho \sim r^{-n}$;
core mass fraction~ (n-3)/n, core KE fraction ~ (n-5)/n

Time dependent ionization balance, radiative and adiabatic losses, electron-ion temperature equilibration via Coulomb collisions

Adjust explosion energy, ambient density, ejecta mass, n, to match forward shock velocity, radius and shocked CSM emission measure (n_e^2V).

Good agreement with Chevalier & Oishi (2003), who take n=10.12

BLASPHEMER

BLASt Propagation in Highly Emitting EnviRonment (sorry!)

Couple Truelove & McKee hydro to ionization/recombination for atomic elements, necessary for interpretation of Chandra spectra (Carles Badenes – Friday)

Neglect collisionless electron-ion equilibration, Coulomb collisions only (Parviz Ghavamian, Sandra Chapman – Thursday, Cara Rakowski – Friday)

Plot electron temperature against ionization age, and compare with knots fits…

Table of Hydro Models for Cas A

Table 1. Cas A Ejecta Profile Models $M_{ej} = 2M_\odot$, $E_{51} = 2$, $\rho r_b^2 = 14$

n	v_b (320yrs) km s^{-1}	r_b (320yrs) pc	η[a]	r_r (320yrs) pc	r_b/r_r	v_{core}[b] km s^{-1}	t_{core}[c] yrs	t_{conn}[d] yrs	t_{rad}[e] yrs	M_{rad}[f] $M_\odot$
5.5	3928	1.79	0.72	1.08	1.66	5795	71.8	92930	-	0
6	4698	2.04	0.75	1.17	1.75	7482	39.5	1162	-	0
7	5239	2.27	0.76	1.29	1.76	9163	18.6	221	-	0
8	5177	2.32	0.73	1.44	1.62	10038	11.0	133	9.25-15.5	0.26
9	5153	2.35	0.72	1.59	1.48	10581	7.3	101	5.35-16.5	0.50
10	5139	2.36	0.71	1.74	1.36	10953	5.2	84.0	3.45-17	0.60
11	5129	2.37	0.71	1.87	1.27	11223	3.93	73.1	2.45-17.5	0.66
12	5121	2.37	0.71	2.00	1.19	11429	3.07	65.5	1.815-18	0.70

[a]Forward shock expansion parameter.

[b]Free expansion velocity of ejecta core-envelope boundary.

[c]Time following explosion when reverse shock enters ejecta core.

[d]Time when blast wave solutions are connected.

[e]Time interval for which ejecta passing through the reverse shock cools to optically emitting temperatures within 320 years.

[f]Mass of gas that can cool to optically emitting temperatures within 320 years of explosion.

Models specified to give same blast wave radius and core density

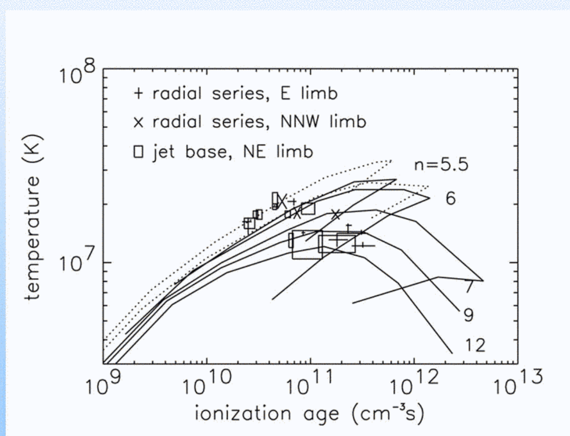
Table 1. Models $r_b = 2.35$ pc, $\rho_{core} = 2.25e6$ g cm^{-3}s^3, and $\rho r_b^2 = 14$ H atom cm^{-3} pc^2

n	M_{ej} $M_\odot$	E_{51} 10^{51} ergs	v_b (320yrs) km s^{-1}	r_b (320yrs) pc	η[a]	r_r (320yrs) pc	r_b/r_r	$M_{ej}(n-3)/n/v_{core}^3$[b] g cm^{-3}s^3
5.5	1.815	4.15	5134	2.345	0.716	1.28	1.92	2.146e6
6	1.815	2.8	5395	2.347	0.752	1.21	1.94	2.248e6
7	1.875	2.15	5338	2.349	0.744	1.29	1.82	2.256e6
8	1.95	2.05	5212	2.349	0.726	1.44	1.63	2.223e6
9	2	2	5153	2.345	0.719	1.59	1.48	2.240e6
10	2.035	1.985	5130	2.348	0.715	1.73	1.36	2.238e6
11	2.065	1.965	5105	2.347	0.712	1.85	1.27	2.267e6
12	2.075	1.95	5085	2.347	0.709	1.96	1.20	2.267e6

[a]Forward shock expansion parameter.

[b]Ejecta core density in velocity space.

Results: O rich Knots

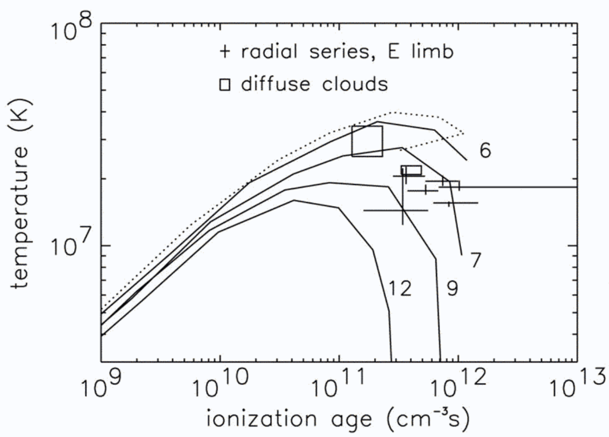


The figure shows T_e against $n_e t$ for varying ejecta envelope power laws. The models are pure O and have:

Ejecta mass = $2M_{Sun}$
K.E. = 2 x 10^{51}ergs
Dens. x r_b^2
= 14 H atoms cm^{-3}pc^2

Jet base knots favour n=5.5-6, higher n elsewhere.

Results: Fe rich Knots

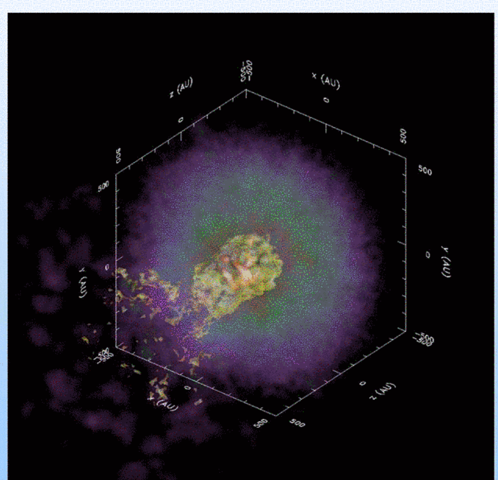


T_e against n_et with Fe:Si composition 9:1 by mass.

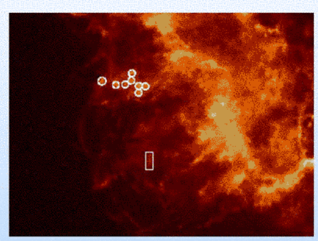
Knot n_et's place them 0.7-0.9 M_{sun} out into the ejecta (mass coordinate ~ 2 M_{sun} including compact remnant), i.e., well outside inner Fe core.

We see a few % of total Fe expected. Most of it must still be inside the reverse shock.

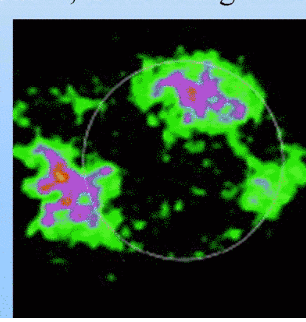
How do the Fe knots form?



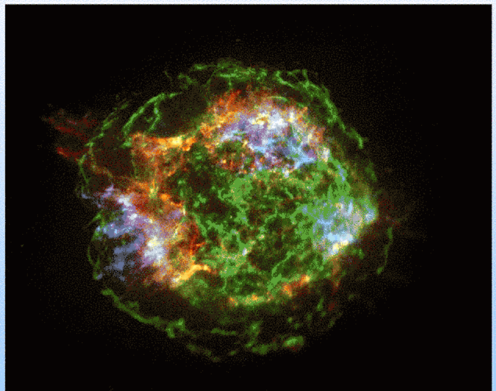
LA-UR-04-5940, courtesy Aimee Hungerford



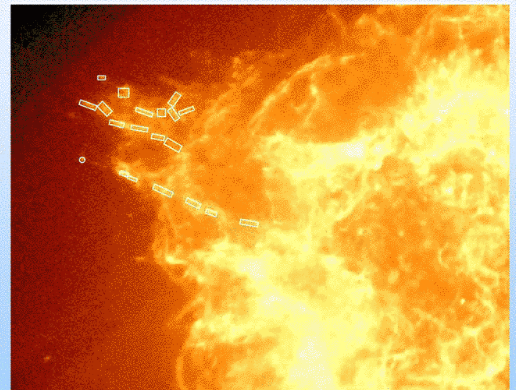
Fe in Cas A, Una Hwang 2001/2003



Cas A in 1 Ms Chandra Image (see Hwang et al. 2004)

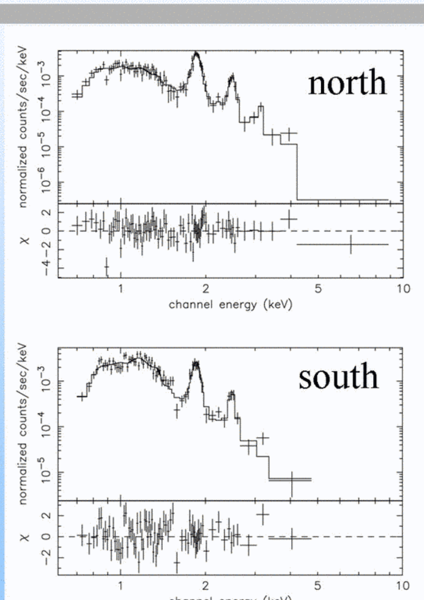


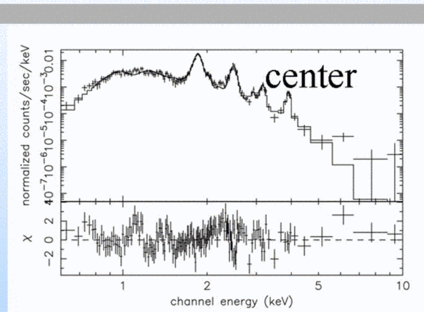
Most of the 3 x 10^8 photons, color coded:
red - He-like Si, blue – He-like Fe, and green – continuum 4-6 keV



Close up of the NE jet region, showing spatial regions from which spectra were extracted.
Blast wave not visible in jet region?

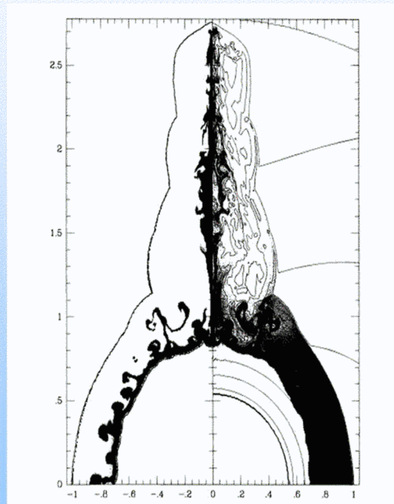
Spectra of the Outermost Jet Knots



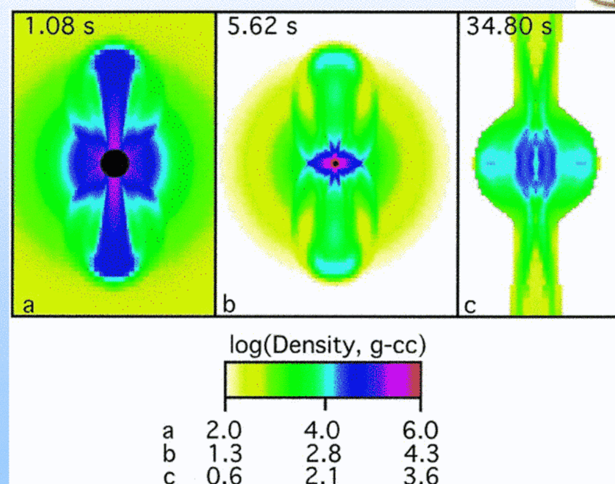


All spectra fit with single T_e and ionization age ($n_e t$), assuming that shock heats knot in time << age of SNR. Ionization ages are the largest we have ever found in Cas A, of order 10^{13} cm^{-3}s. Plasma is very close to collisional ionization equilibrium.

Is the Cas A polar morphology due to csm cavities (e.g Blondin, Lundqvist & Chevalier 1996), jets (e.g. Khokhlov et al. 1999), …

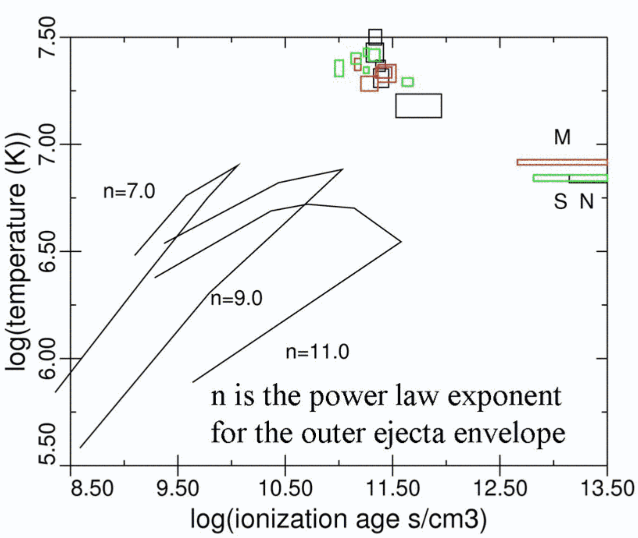


From Blondin et al. (1996)



From Khokhlov et al. (1999)

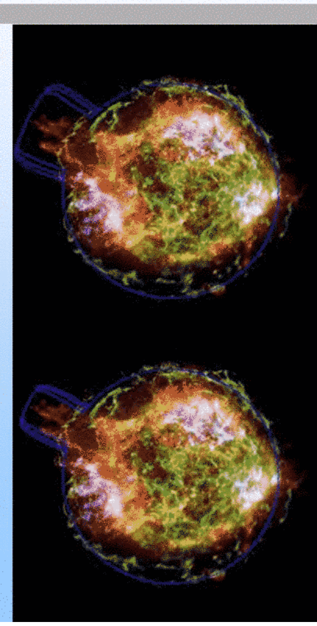
T_e against $n_e t$ for Cavity models



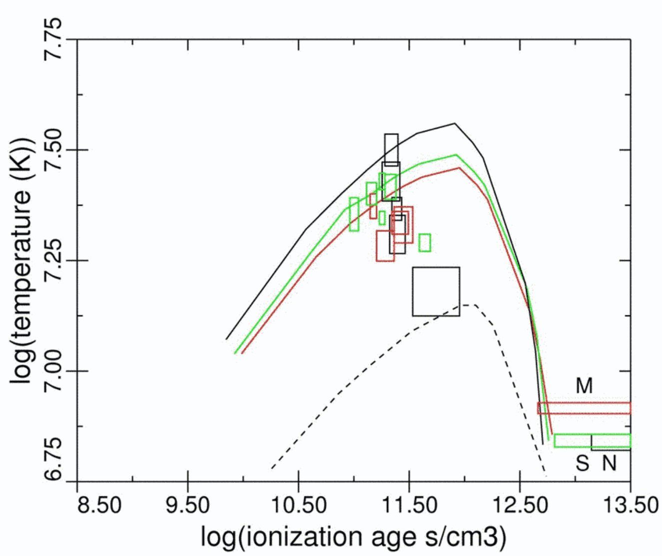
Maximum $n_e t$ is $\sim 4 \times 10^{11}$ cm^{-3} s, and is unable to match knots at the jet tip.
Put another way, cavities do not have sufficient plasma density in polar regions to drive knots to collisional ionization equilibrium,
→Asymmetric explosion is required!

Jet Models

- Use self similar model from Truelove & McKee (1999) with ejecta density ~ r^{-1}.
- Equivalent spherical ejecta mass = 1.815 solar masses,
- Equivalent isotropic energy=2.3×10^{52} ergs.
- Total jet energy is ~ 10^{50}ergs for jet opening angle of 7 degrees (see bottom panel at right). Too low to have actually been a gamma ray burst, by at least an order of magnitude.



T_e against $n_e t$ for Jet models



Same knot fits as before, different jet models to match fit element abundances in N, M, and S.

Dashed line shows N knot with H dominated Composition.

Much better match to observations than with cavity models.

How Does the "Jet" Sustain Itself in SNR Phase?

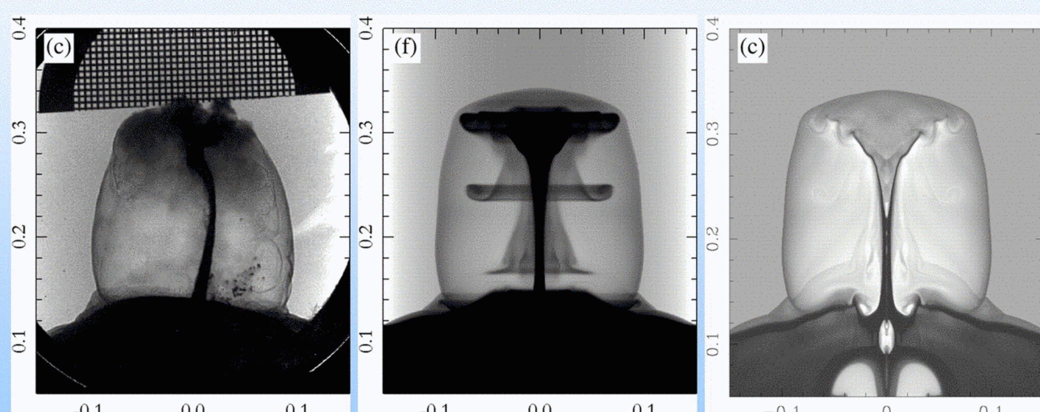
According to Kompaneets approximation, pressure behind blast wave should equilibrate in Sedov-Taylor phase and blast wave should become spherical.

Answers.....

1. Because of nonradial flow of shocked circumstellar medium in jet region, jet remains ejecta dominated much longer.
2. There are always cold ejecta in the jet region, either unshocked ejecta at early times or reverse shocked ejecta that have cooled by radiation at later times (especially if the plasma composition at the jet head is dominated by Fe as we suspect), which also inhibits pressure equilibration. There is always a cold "bullet" of material pushing the jet out.

Detailed hydrodynamic simulations of such SNR jets are planned, with and without radiative cooling.

Complications in the jet – Foster et al. 2005, ApJ, 634, L77



Jet(s) produced at OMEGA (LLE Rochester) and hydro simulations; clearly we need multi-D hydro (Khokhlov, Dominguez, ...)

Concluding Thoughts

- The "knots" in Cas A turn out to be crucial, in many ways….
- Unusual application of atomic physics – the *ionization balance is the crucial diagnostic*
- We are trying to understand "big picture" variables – explosion energies, asymmetries, pulsar natal kick,… for which the only other observables are neutrinos (detected in SN 1987A) and gravitational waves (never detected), and less directly, pulsar spins and space velocities.
- Contrast with "traditional" spectroscopic diagnostics, measure electron density, temperature, etc.