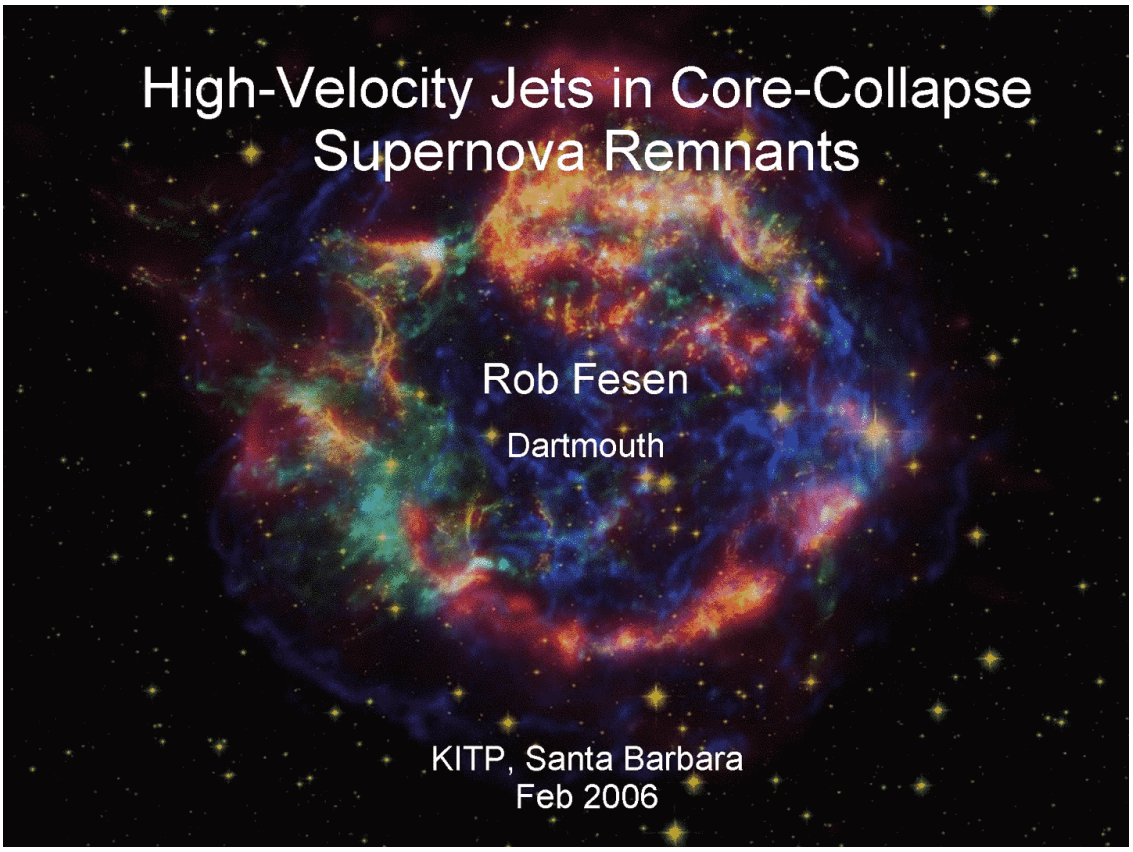


Compared to SN observations, evidence for aspherical core-collapse explosions based on supernova remnant observations is much less clear.

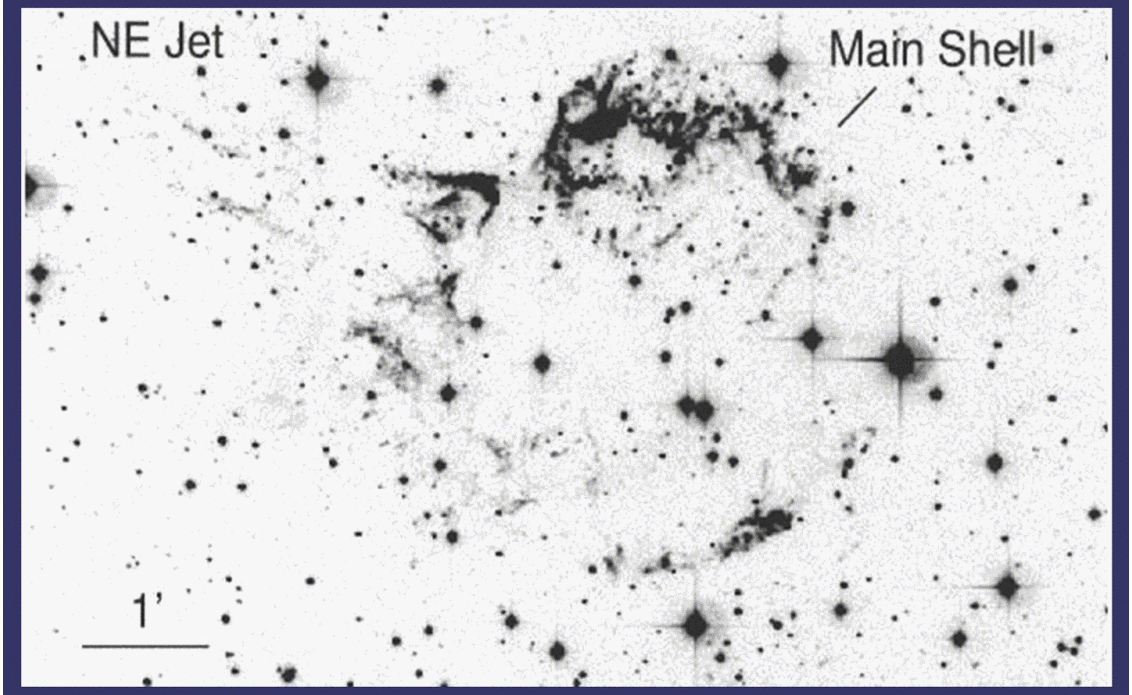
However, the distribution of high-velocity, metal-rich ejecta in young Galactic core-collapse supernova remnants offers us information on much finer spatial scales than possible from extragalactic SNe or SNR studies.

One of the most often cited asymmetrically expanding SNRs is that of Cassiopeia A (Cas A).

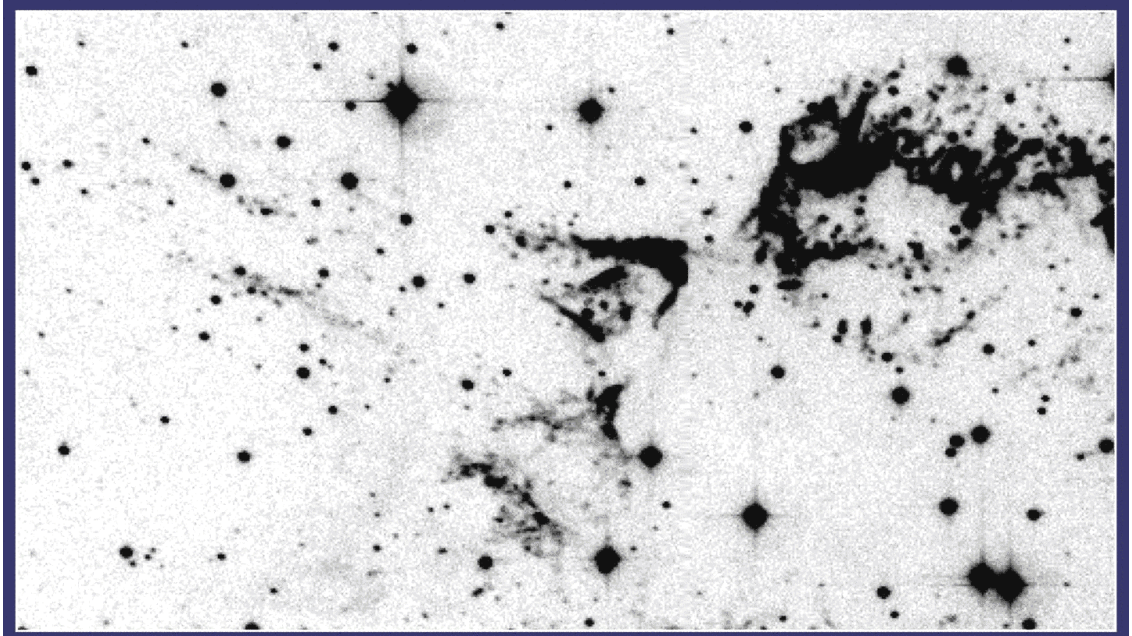
Cas A

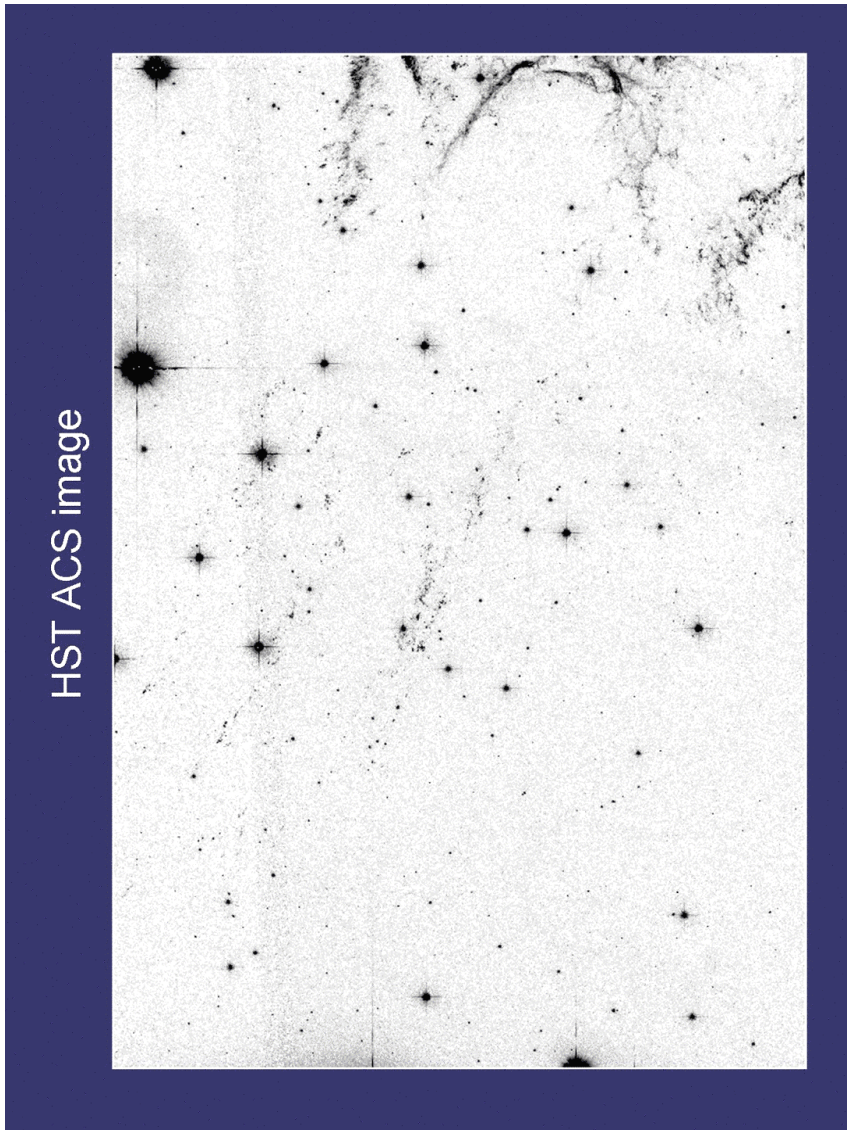
- Age: ~300 yrs; Remnant of SN 1680 +/- 20
- Extreme O- and Si-group abundances in so-called “Fast-Moving Knots” (FMKs). V_{exp} = 4500 – 6000 km/s
- X-ray and optical data suggest it is the remnant of a core-collapse of a 20-30 solar mass star.
- Progenitor had a He-rich envelope. Strongly enhanced He and N abundances in “quasi-stationary flocculi” (QSFs). Probably a Wolf-Rayet star (WN).

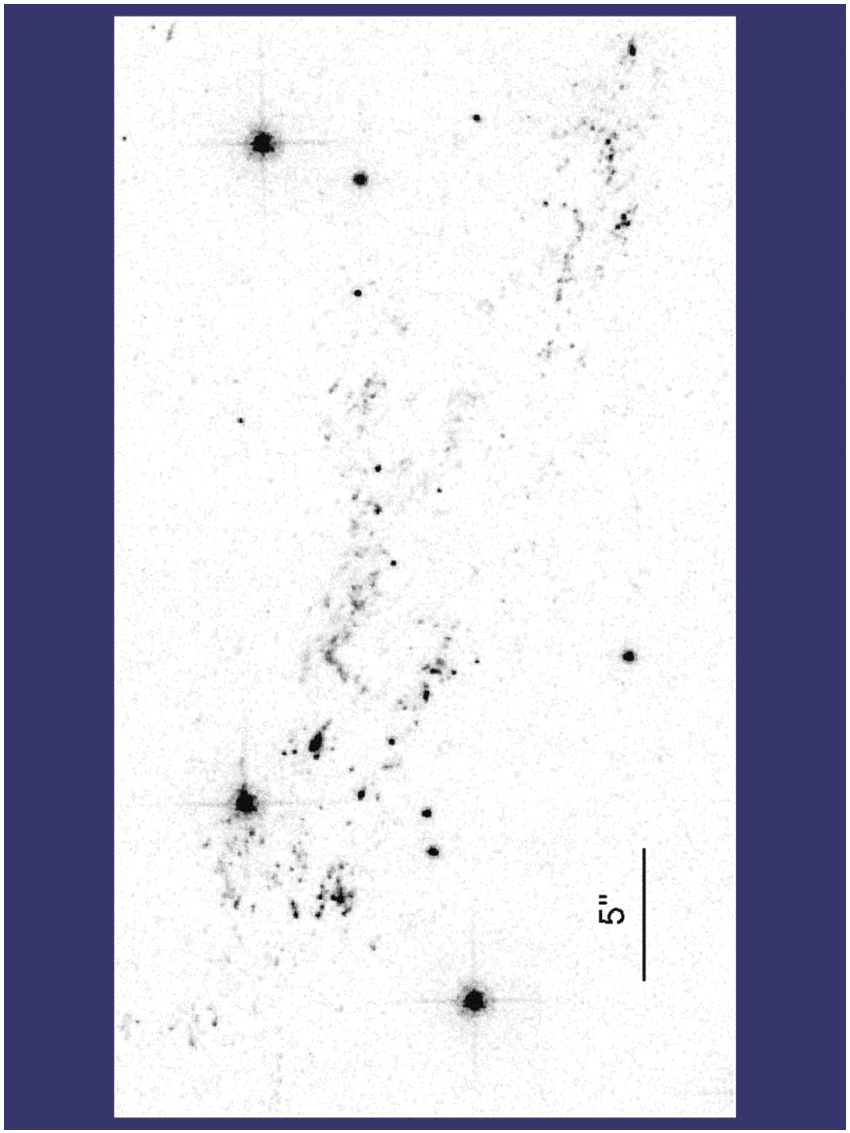
Besides the main emission shell of O-and S-rich debris Cas A shows evidence for much higher-velocity ejecta…maybe Jets.

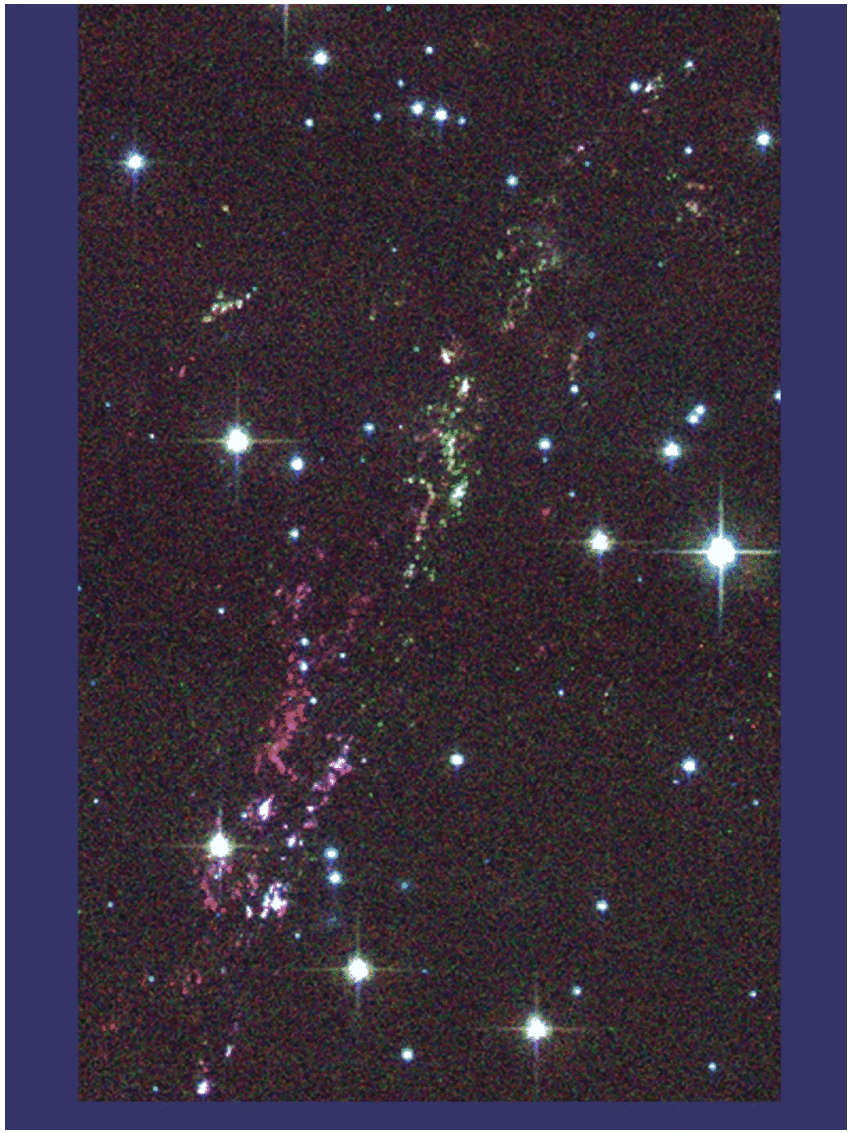


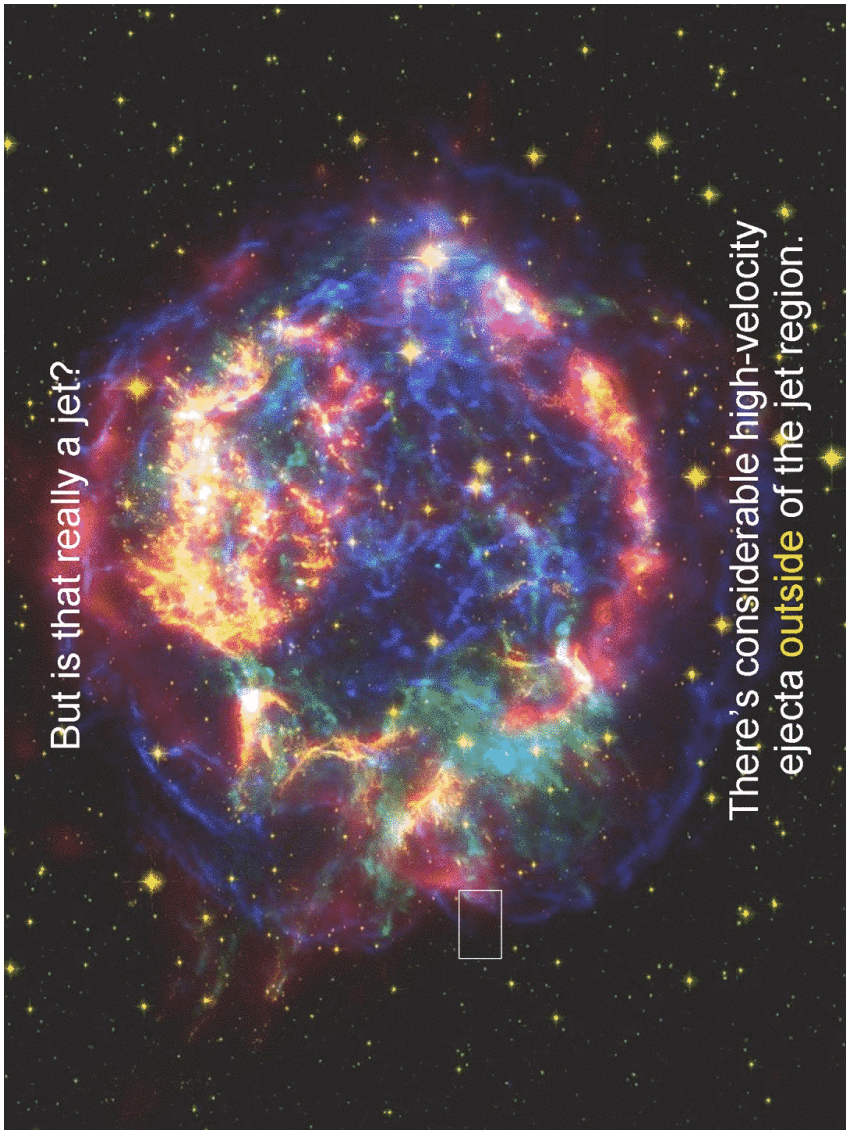
Cas A's so-called Northeast Jet

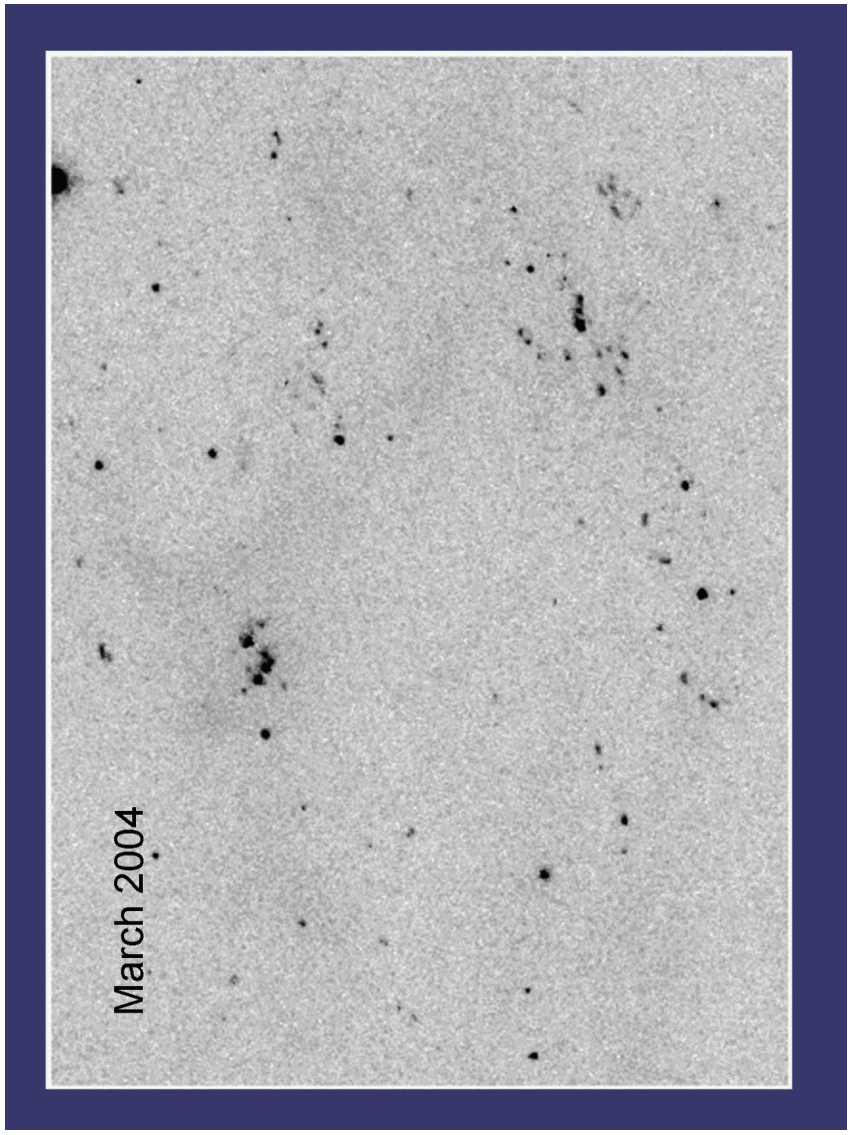


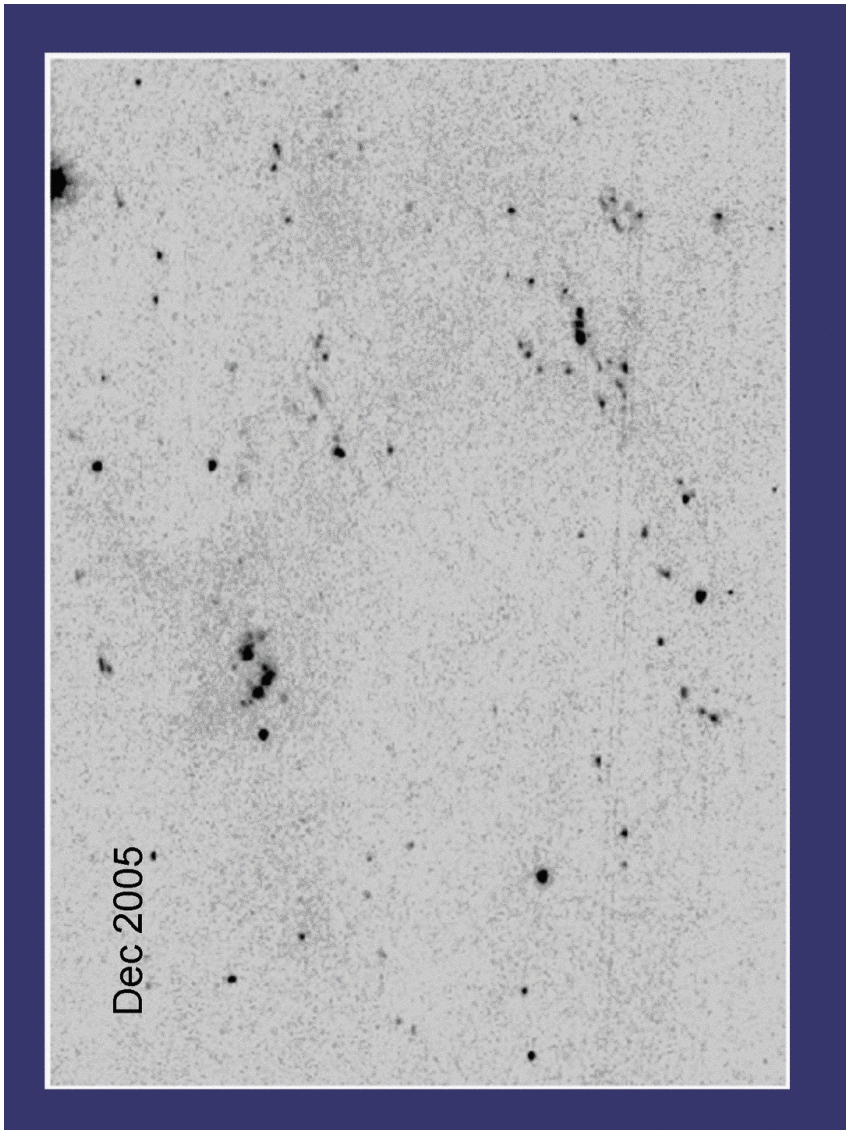

HST ACS image

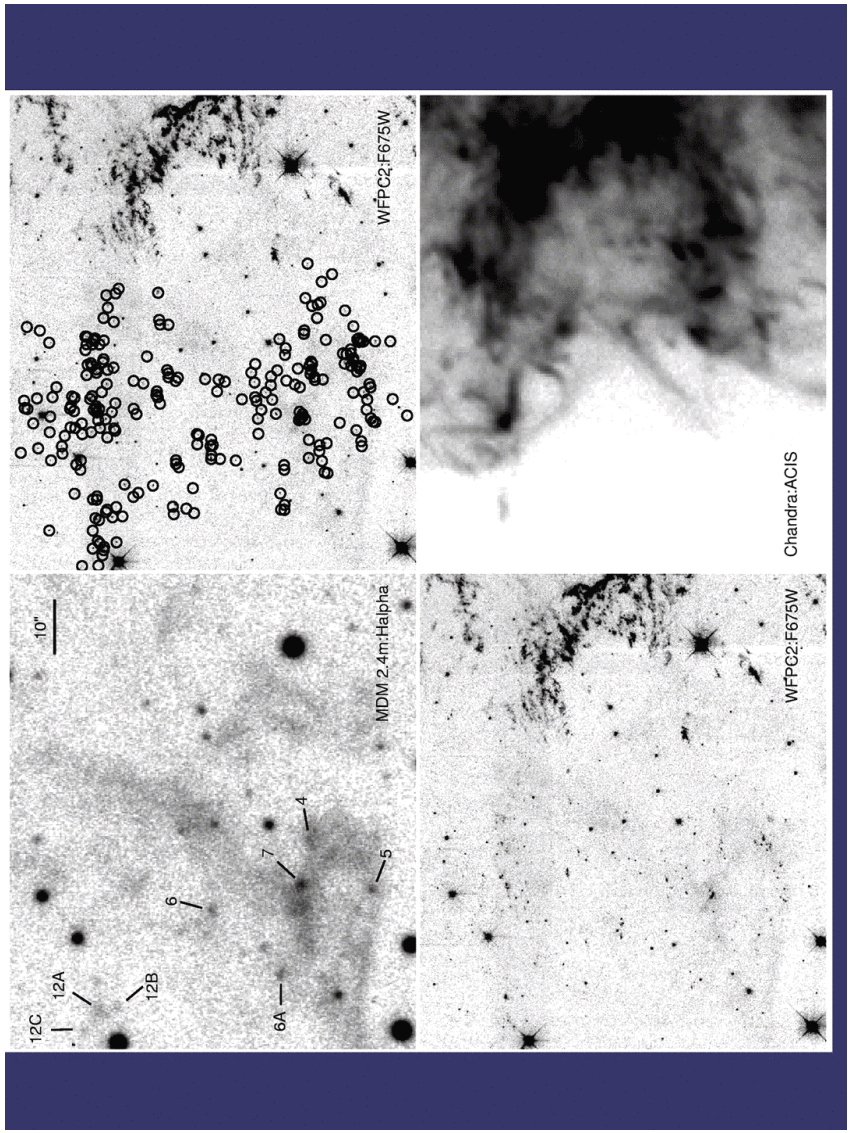

5"

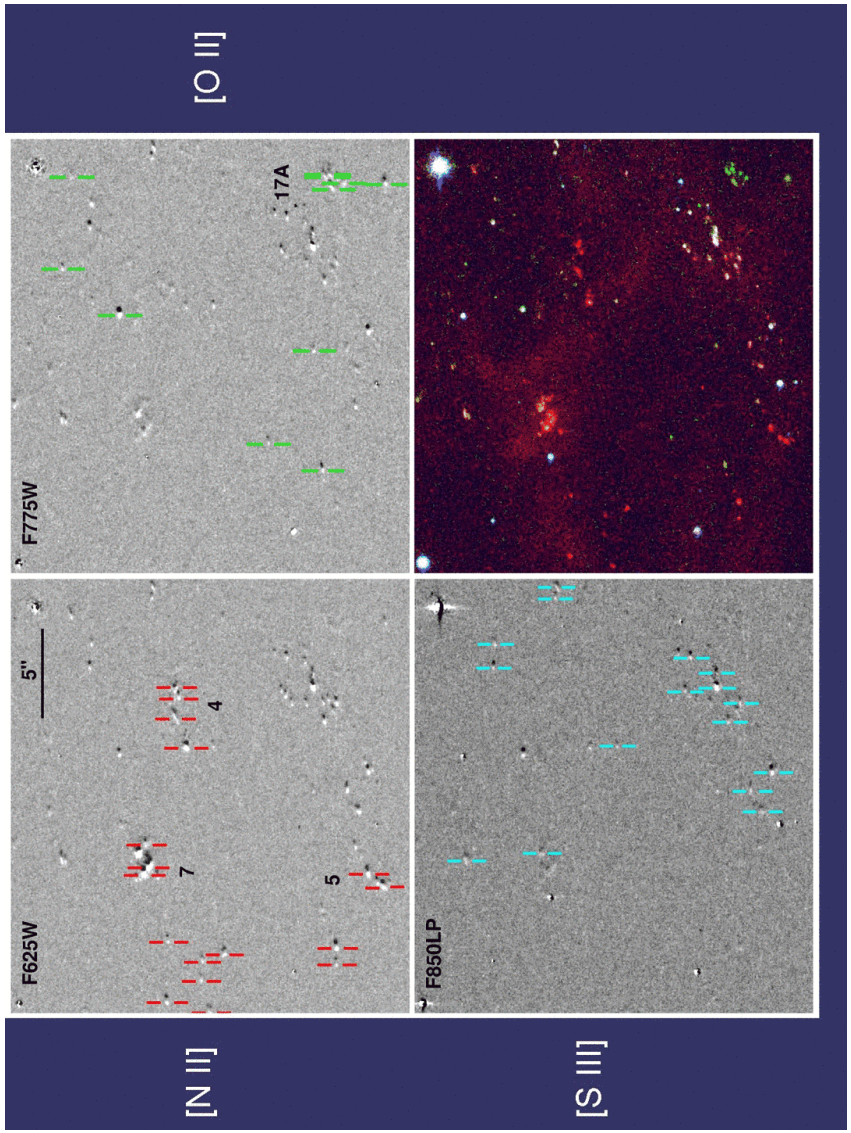


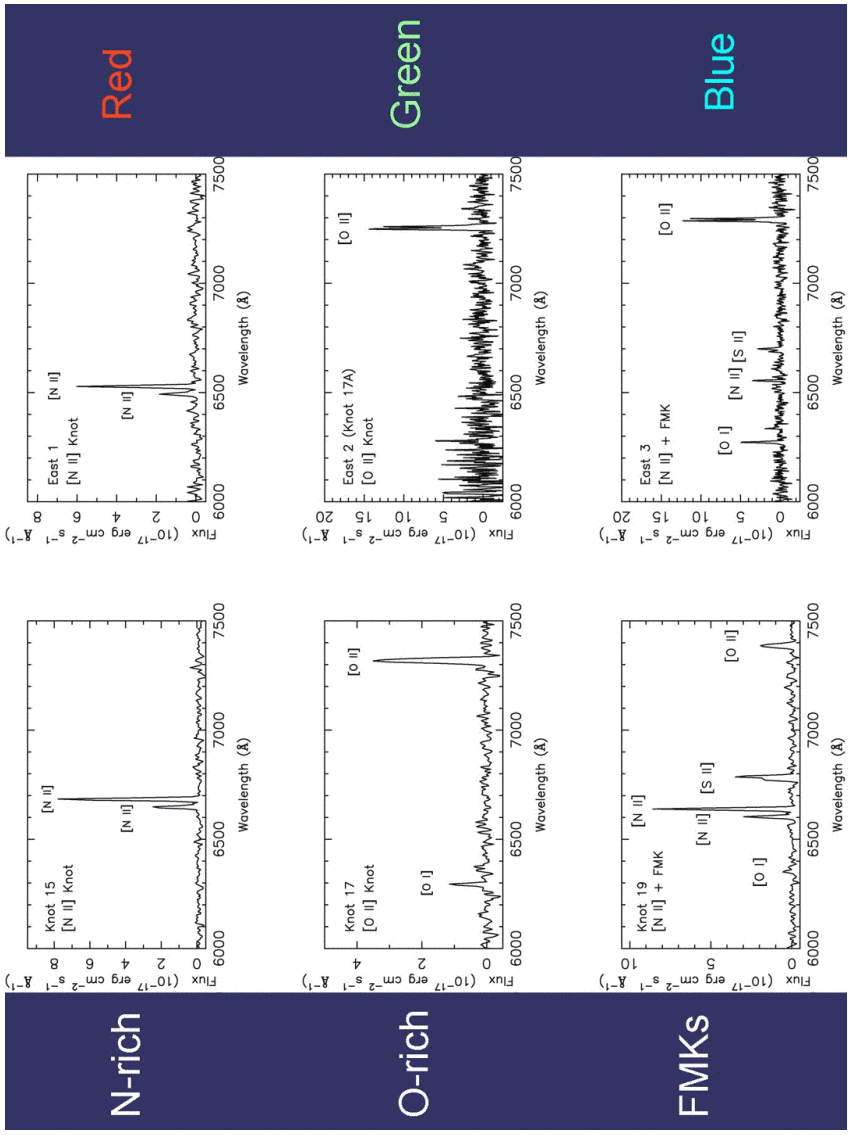

But is that really a jet?
There's considerable high-velocity ejecta outside of the jet region.

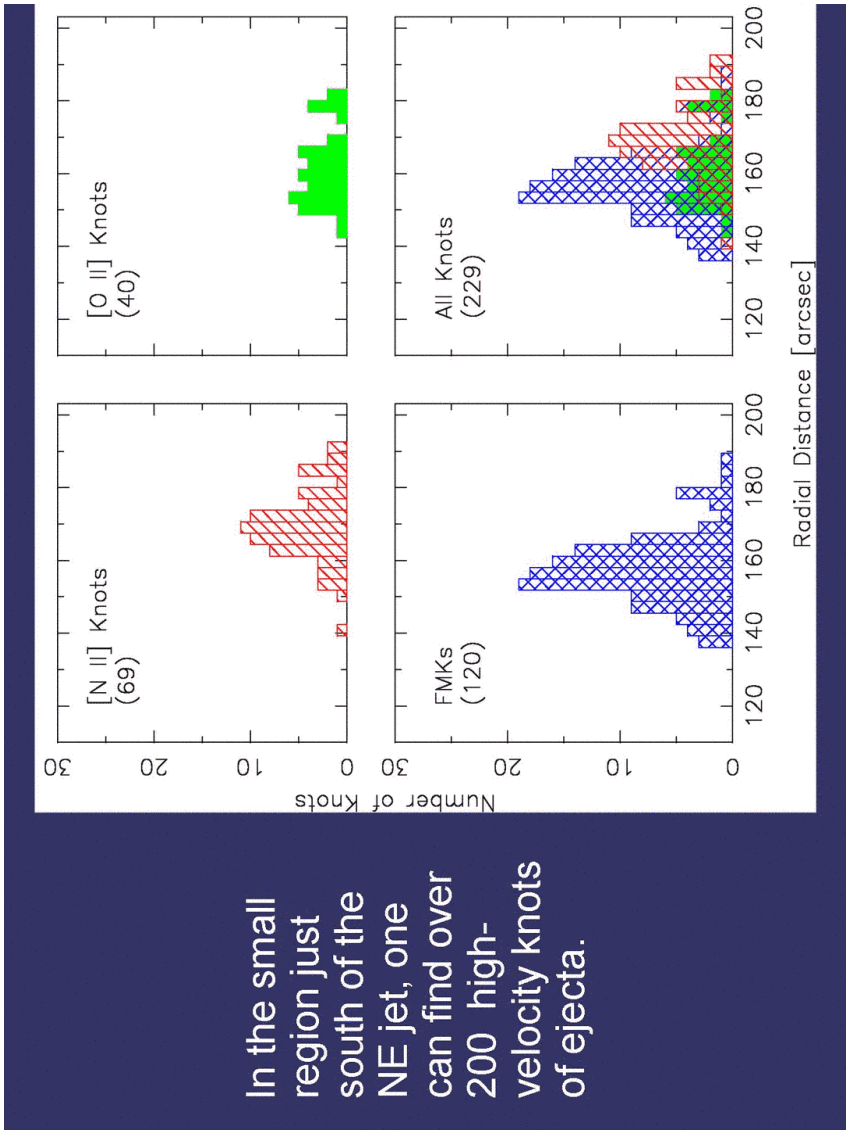

March 2004


Dec 2005


WFPC2:F675W
Chandra:ACIS
MDM 2.4m:Halpha
WFPC2:F675W
10"
12C
12A
12B
6
6A
7
4
5


[O II]
F775W
17A
5"
F625W
4
7
5
F850LP
[N II]
[S III]


Red
Green
Blue
N-rich
O-rich
FMKs
Knot 15
[N II] Knot
East 1
[N II] Knot
Knot 17
[O II] Knot
East 2 (Knot 17A)
[O II] Knot
Knot 19
[N II] + FMK
East 3
[N II] + FMK
[N II]
[O II]
[O I]
[S II]
Flux (10⁻¹⁷ erg cm⁻² s⁻¹ Å⁻¹)
Wavelength (Å)


In the small region just south of the NE jet, one can find over 200 high-velocity knots of ejecta.
[N II] Knots (69)
[O II] Knots (40)
FMKs (120)
All Knots (229)
Number of Knots
Radial Distance [arcsec]

Transverse velocities:

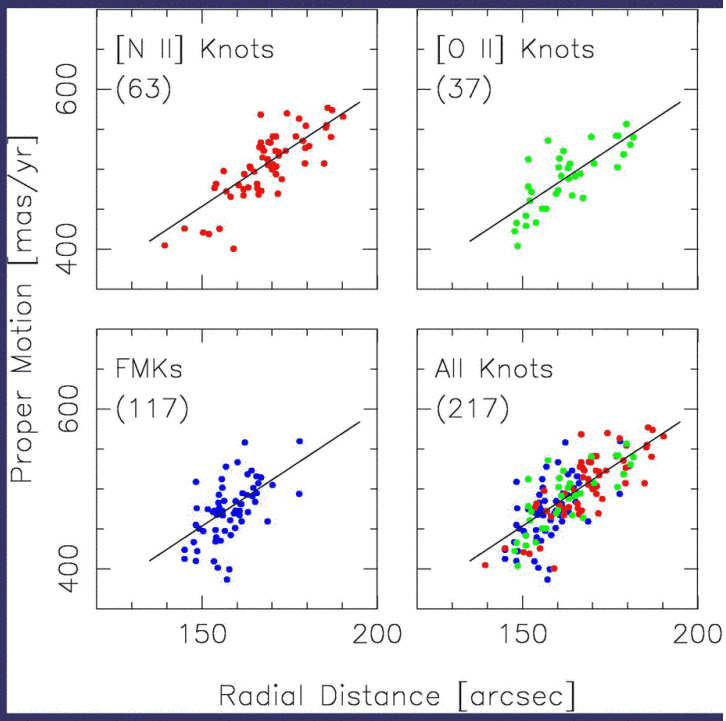
6500 – 9000 km/s

➔ N-rich knots lie out ahead of the O-rich knots which lie at or just a bit out in front of the S-rich FMK-like ejecta.

N-rich: 8100 km/s

O-rich: 7900 km/s

S-rich: 7600 km/s



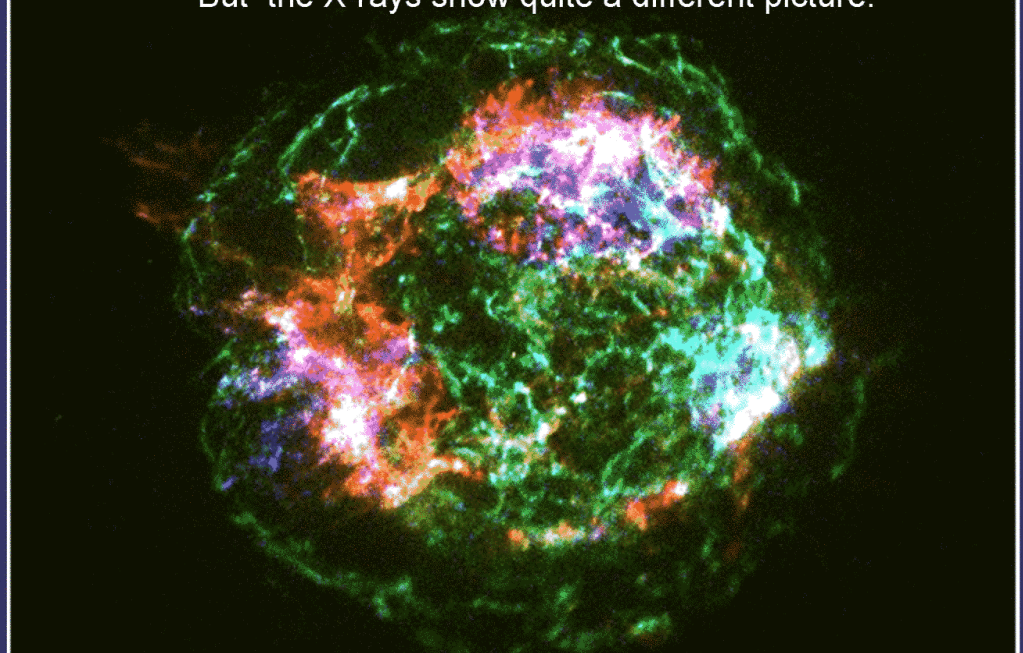
So it would seem that…

The progenitor's original abundance layering of

N-He O S-Si-Ar-Ca

survived the SN explosion dynamics at least for this East-Southeastern region.

But the X-rays show quite a different picture.

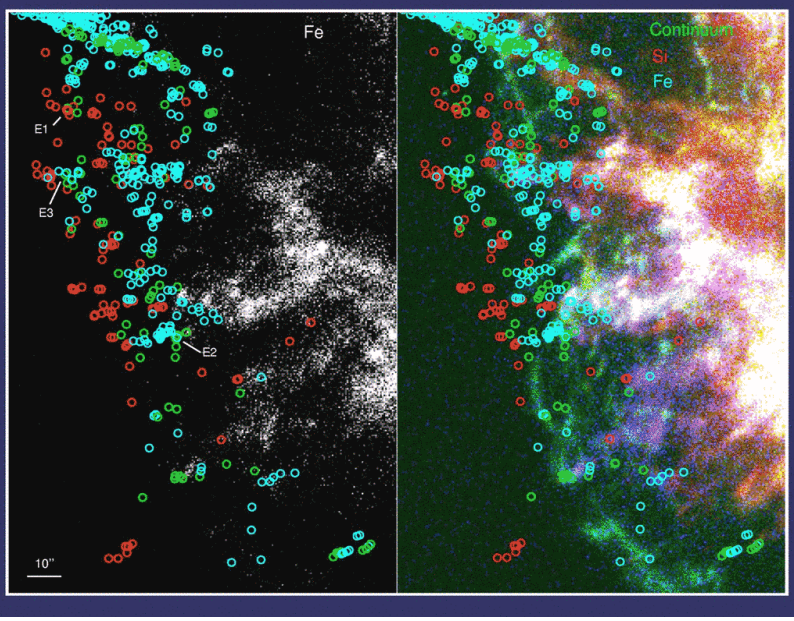


The southeast Fe-rich region (blue) lies out ahead of the Si-rich (red)

Hughes et al. 2000

But...these high-speed optical N,O, and S bright knots lie out in front of the X-ray Fe-rich ejecta.

So: The original outer layering was not disrupted in this region, despite a clear overturning of Si,S and Fe layers deeper down.



So what about that “NE jet” ?

Is it really a jet at all?

Or just a region where the remnant expanded more rapidly due to a less strong circumstellar interaction?

Blue: S-rich

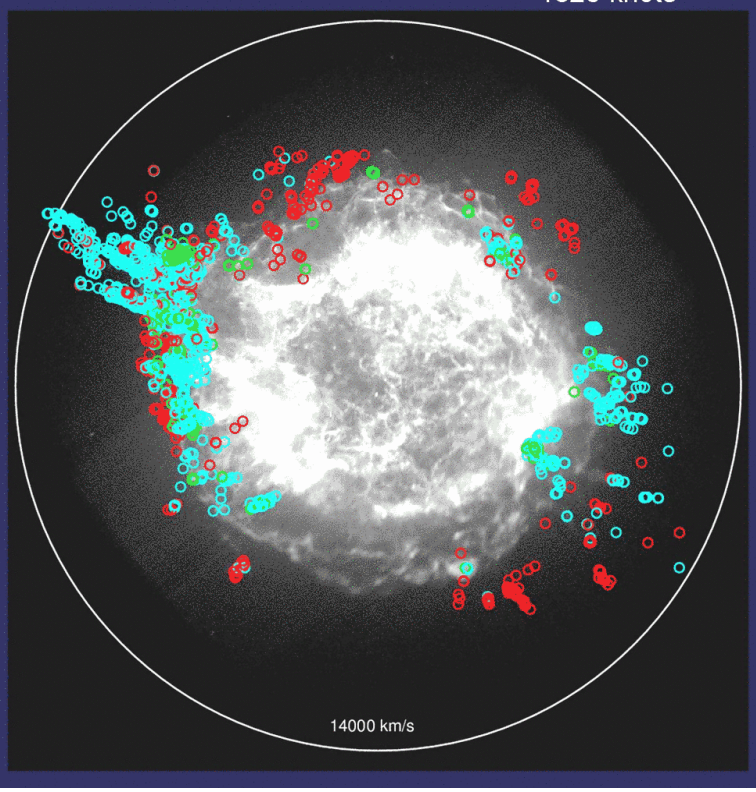
Red: N-rich

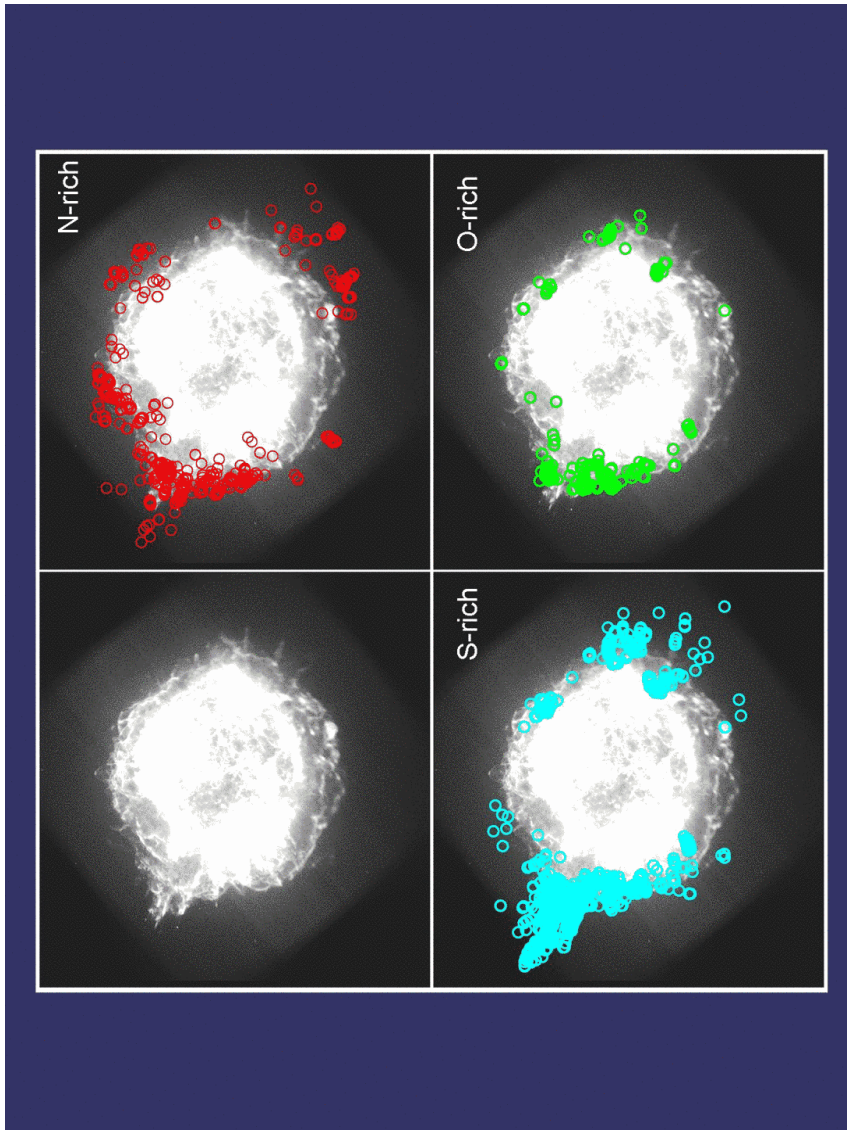
Green: O-rich

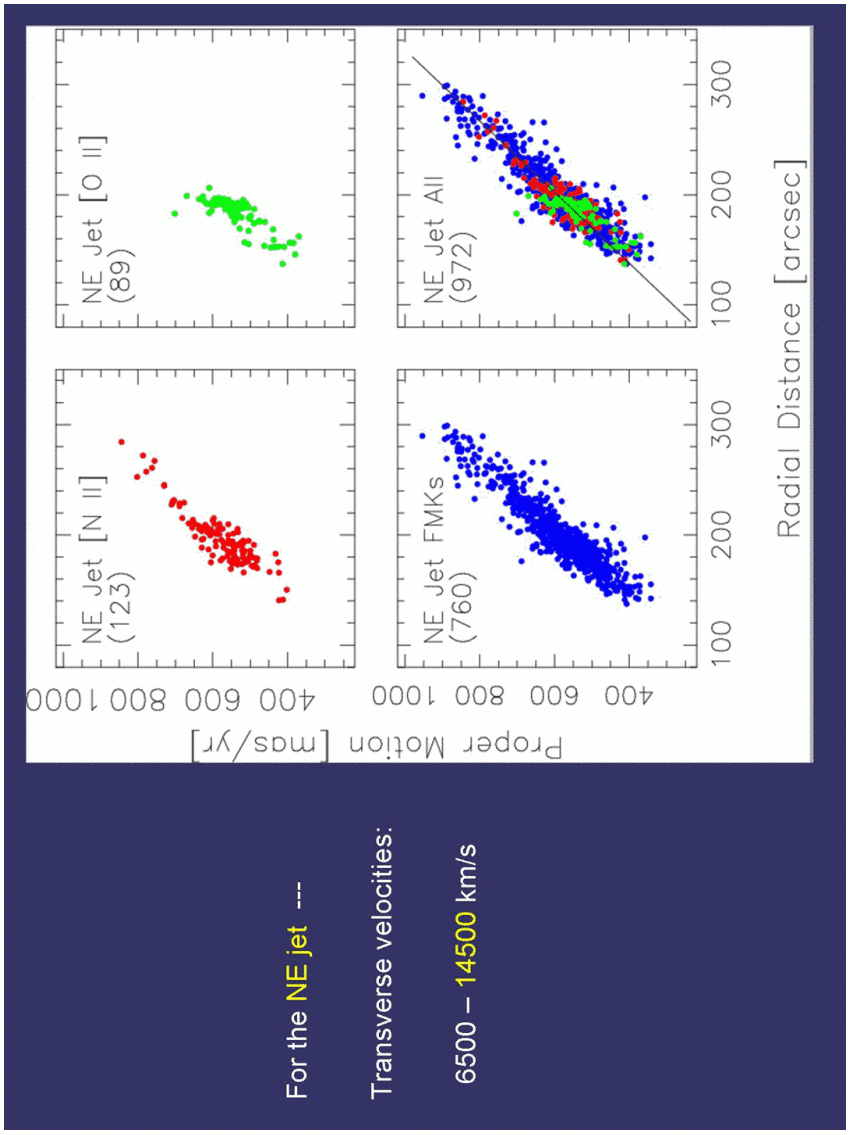
HST/ACS images show:

Two opposing jets of ejecta

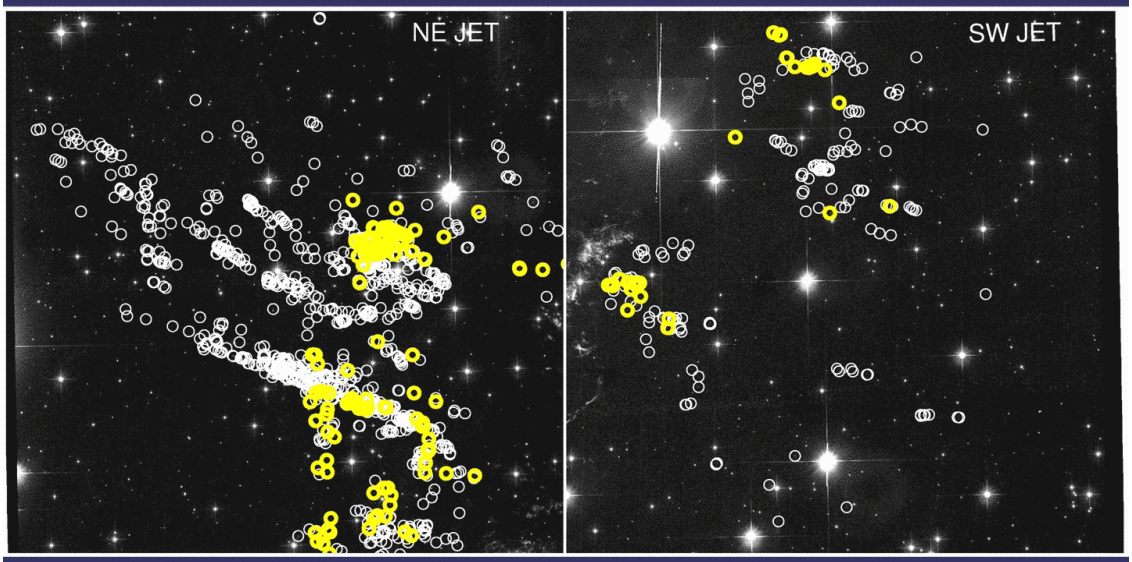
With a different chemistry radially.




N-rich
O-rich
S-rich


NE Jet [O II] (89)
NE Jet All (972)
NE Jet [N II] (123)
NE Jet FMKs (760)
Proper Motion [mas/yr]
Radial Distance [arcsec]
For the NE jet ---
Transverse velocities:
6500 – 14500 km/s

One also sees Oxygen Layer "Hinges" (?)



Clumps of O-rich ejecta near the NE (left) and SW (right) jets

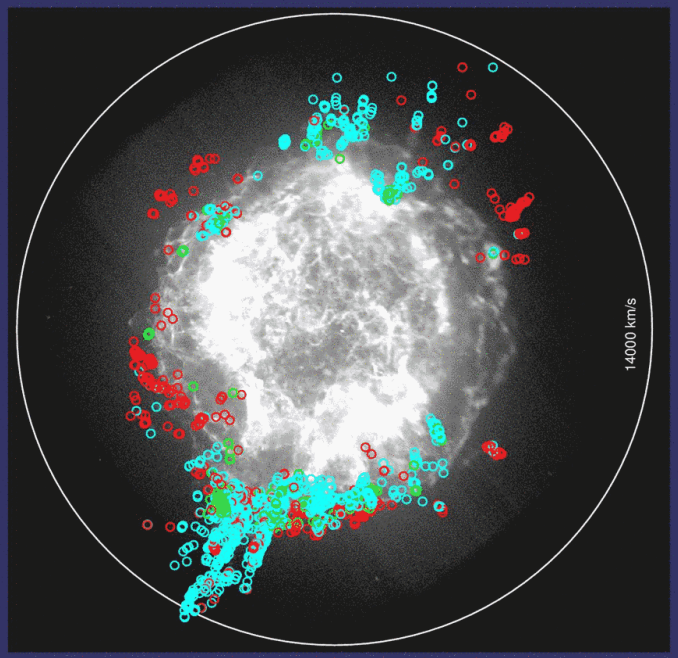
The remnant exhibits two opposing jets of debris having similar maximum expansion velocities.

These jets are not narrow but have opening angles ~ 30 degrees.

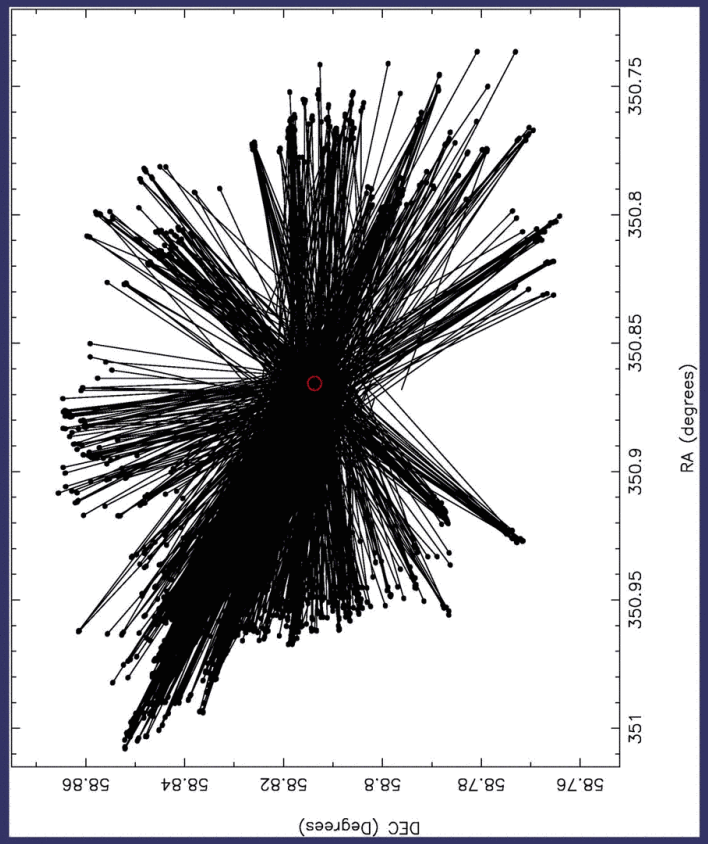
The material located at the farthest tip -- and thus possess the highest ejection velocities -- appear to be S-rich debris likely from the S,Si,Ar-rich mantle, i.e., from deep inside the progenitor star and are not fragments from the photosphere.

So the Cas A remnant really does appear to have high speed plumes of ejecta which are not the result of uneven expansion into the local medium.

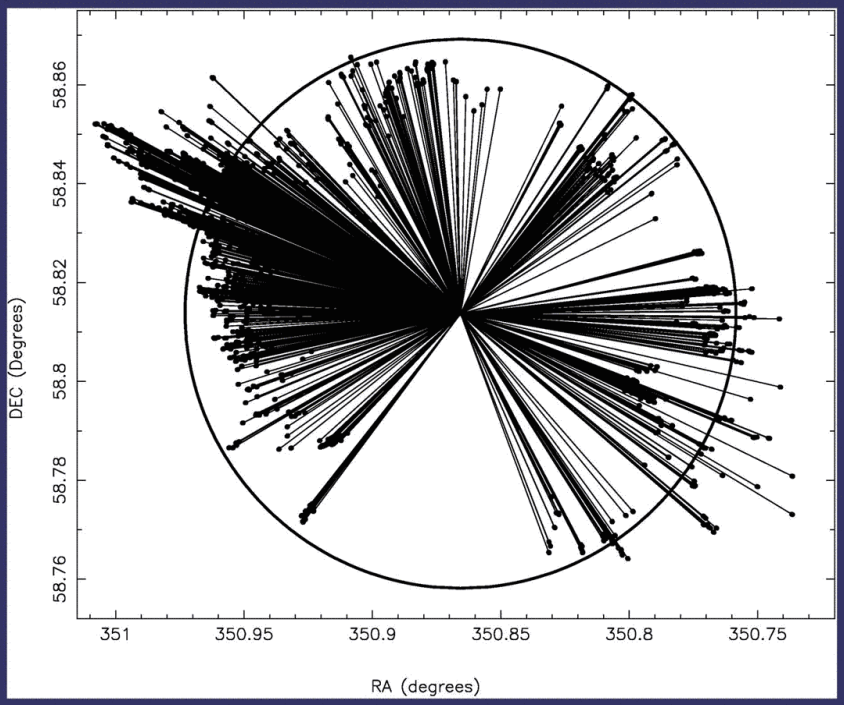
The distribution of the remnant's outermost ejecta knots also suggests an hour-glass shape expansion.



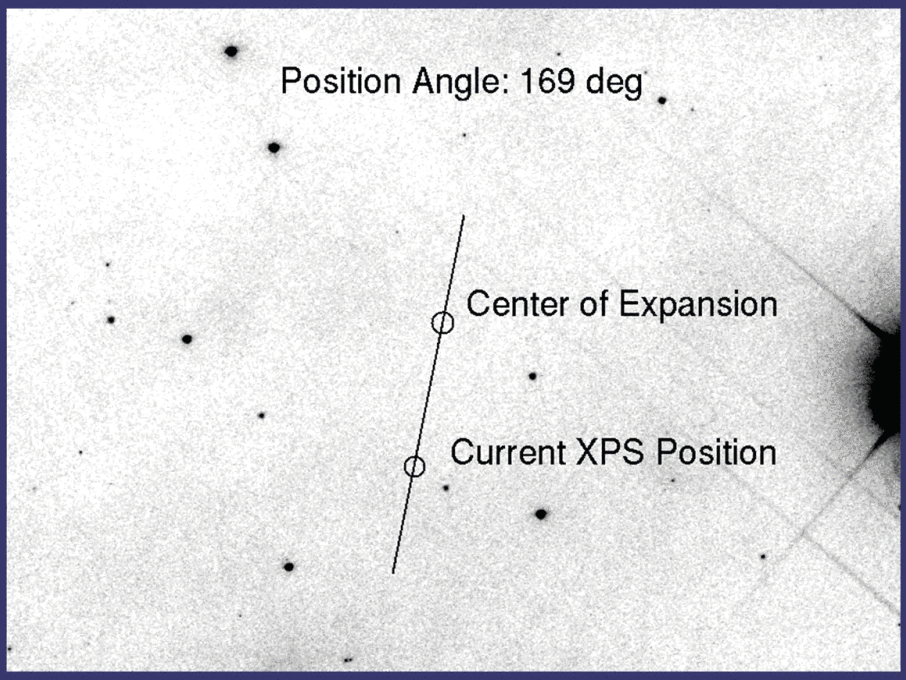
A "kaboom" plot for the 1825 outlying ejecta knots.



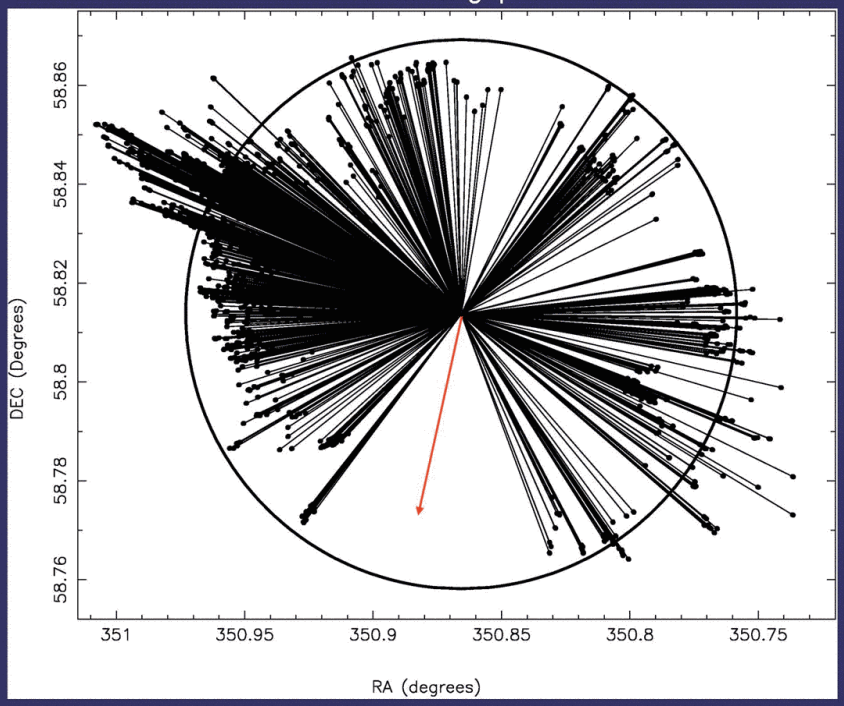
The observed distribution suggests a highly asymmetric bi-polar explosion…one with both jets and orthogonal ejecta gaps.

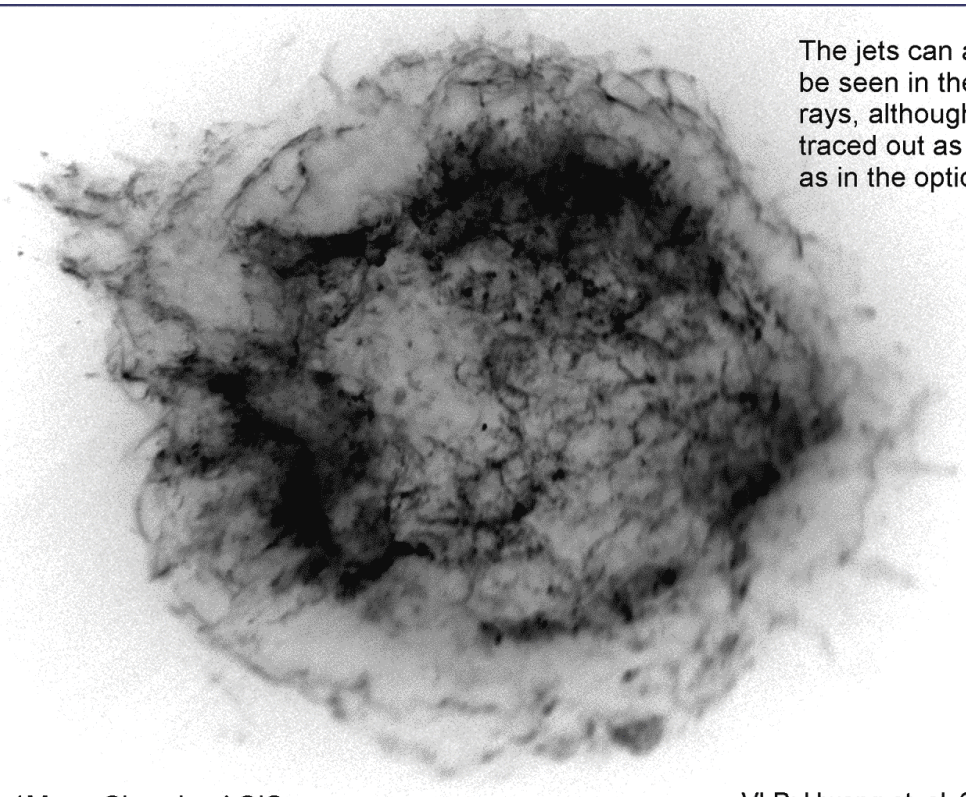


We know both the expansion center and the current XPS position to +/- 0.5 arcsec.



Interestingly, the compact central object is moving toward the southern gap.



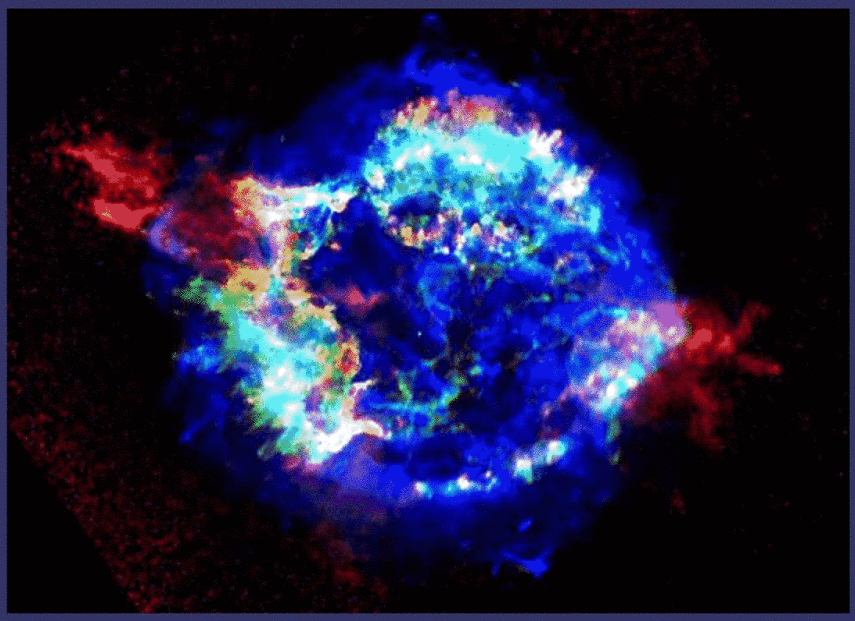


The jets can also be seen in the X-rays, although not traced out as far as in the optical.

1Msec Chandra ACIS

VLP: Hwang et al. 2004

But the X-ray emission properties of the jets show them to be chemically different from the rest of the remnant's outlying ejecta.



Color composition: Red =Jet (Si XIII/Mg XI ratio), Green = Si XIII, and Blue = Radio image

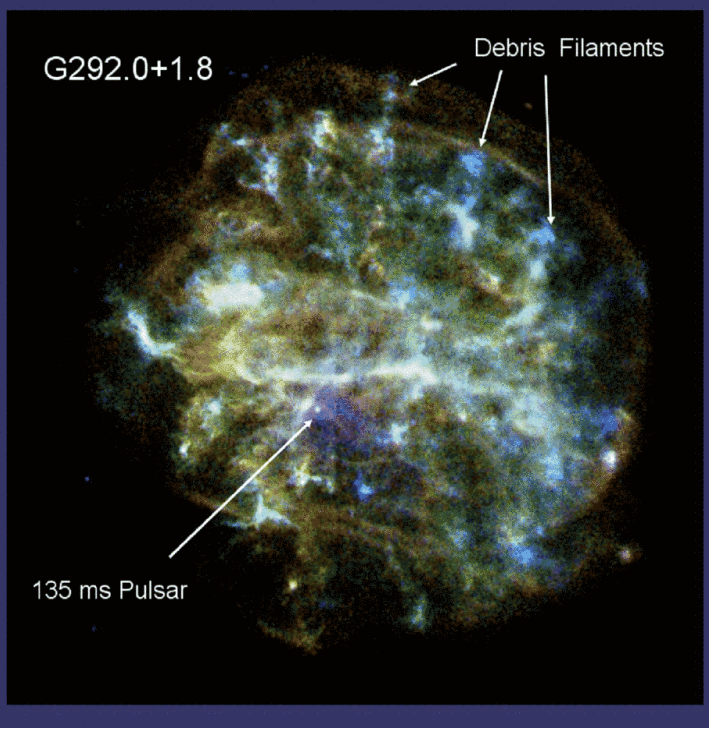
Vink 2004

What about other young, Galactic core-collapse supernova remnants?

Do any of these remnants show jets?

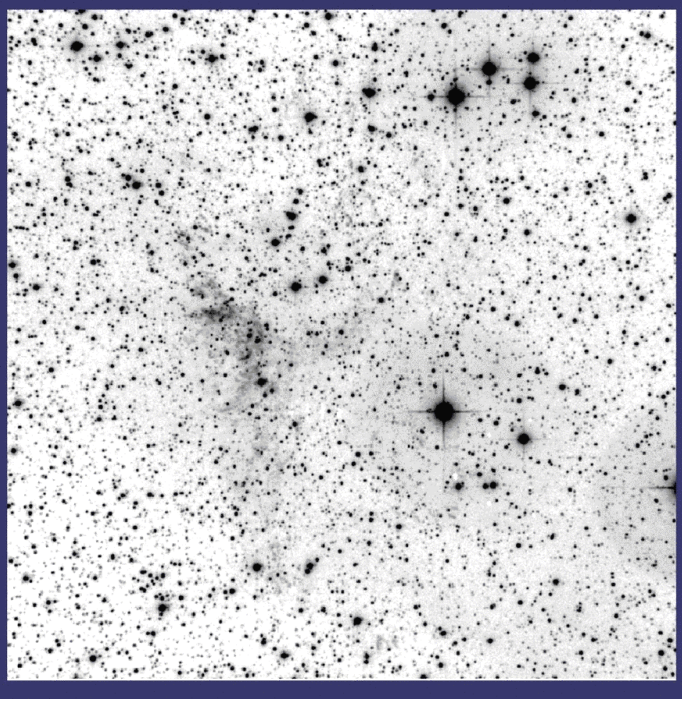
Well…maybe.

The southern hemisphere core-collapse remnant G292.0+1.8 is like Cas A.



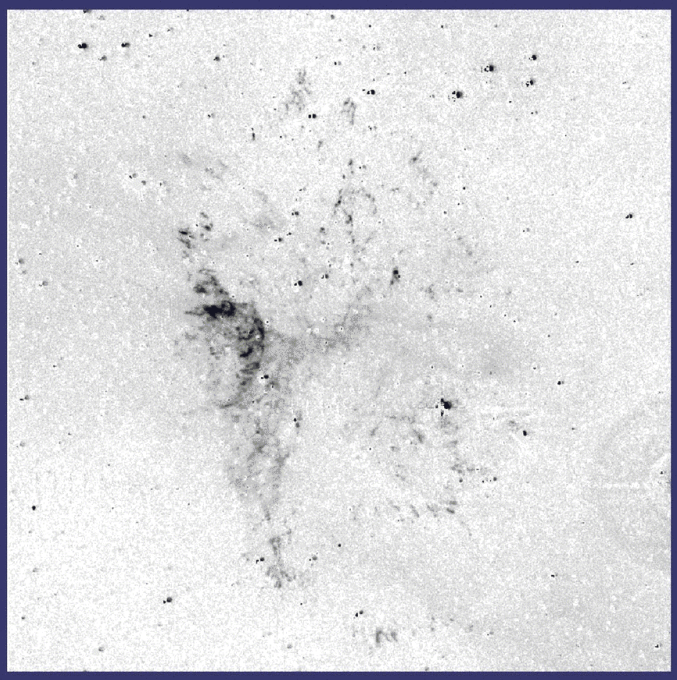
Hughes et al. 2001

It's a bit harder to study in the optical.

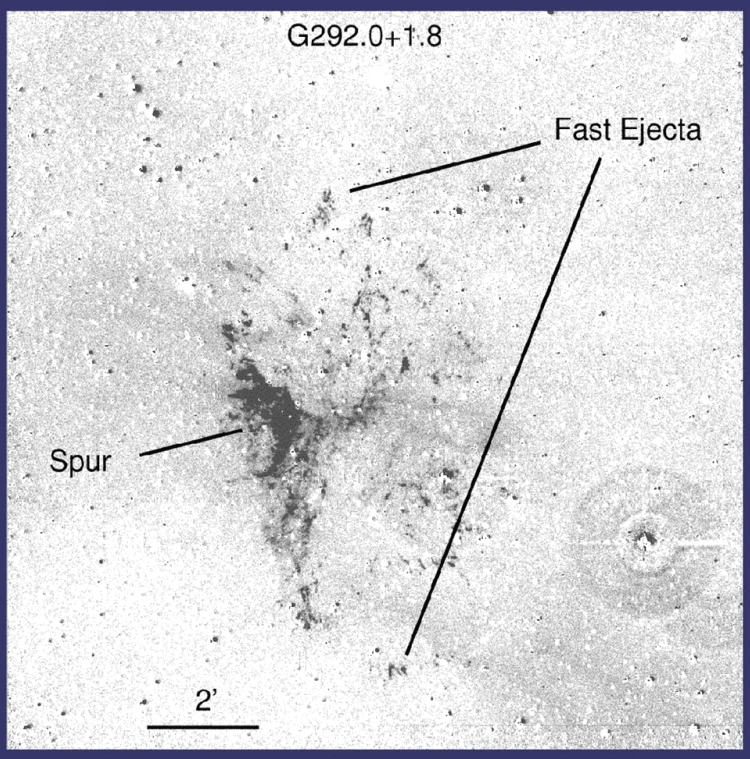


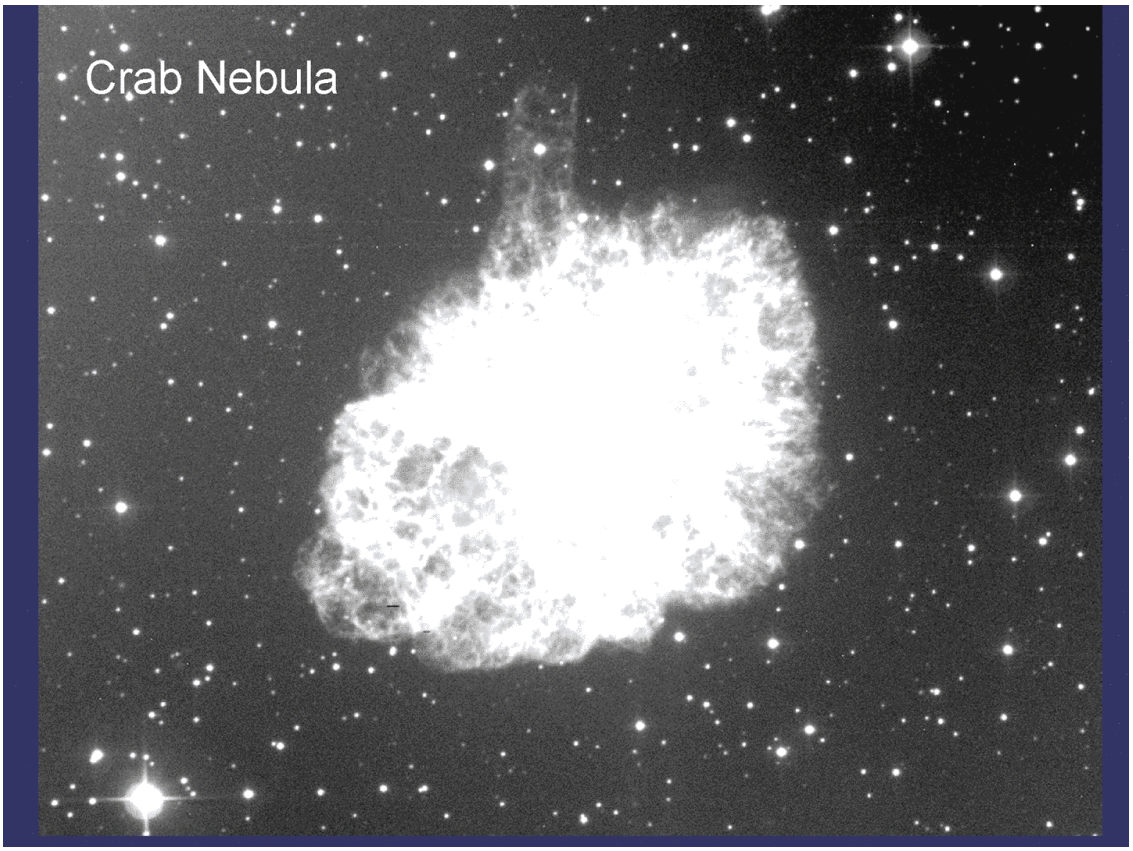
Winkler & Long 2006

But somewhat like Cas A, G292.0+1.8 exhibits O-rich and S-rich ejecta in an aspherical structure.



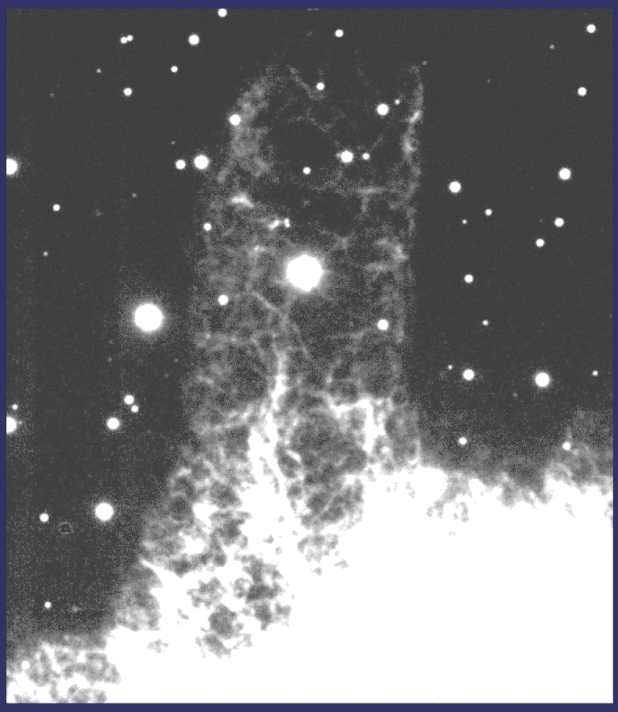
Winkler & Long 2006





This ‘Chimney’ or `Jet’ does have a bit higher expansion velocity than the rest of the Crab.

But it is really what one would call an ejecta jet?



Summary

- Cas A does appear to have two opposing high speed plumes of ejecta (jets) with similar maximum expansion velocities.
- There also appears to be gaps in the distribution of the outermost ejecta perpendicular to the jets.
- Jet material ejected with the highest ejection velocities appear to originate from deeper inside the progenitor star.
- The presence of high-velocity ejecta jets in other young core-collapse SNRs is far less clear. But there is little evidence for narrow beams of high-speed debris.