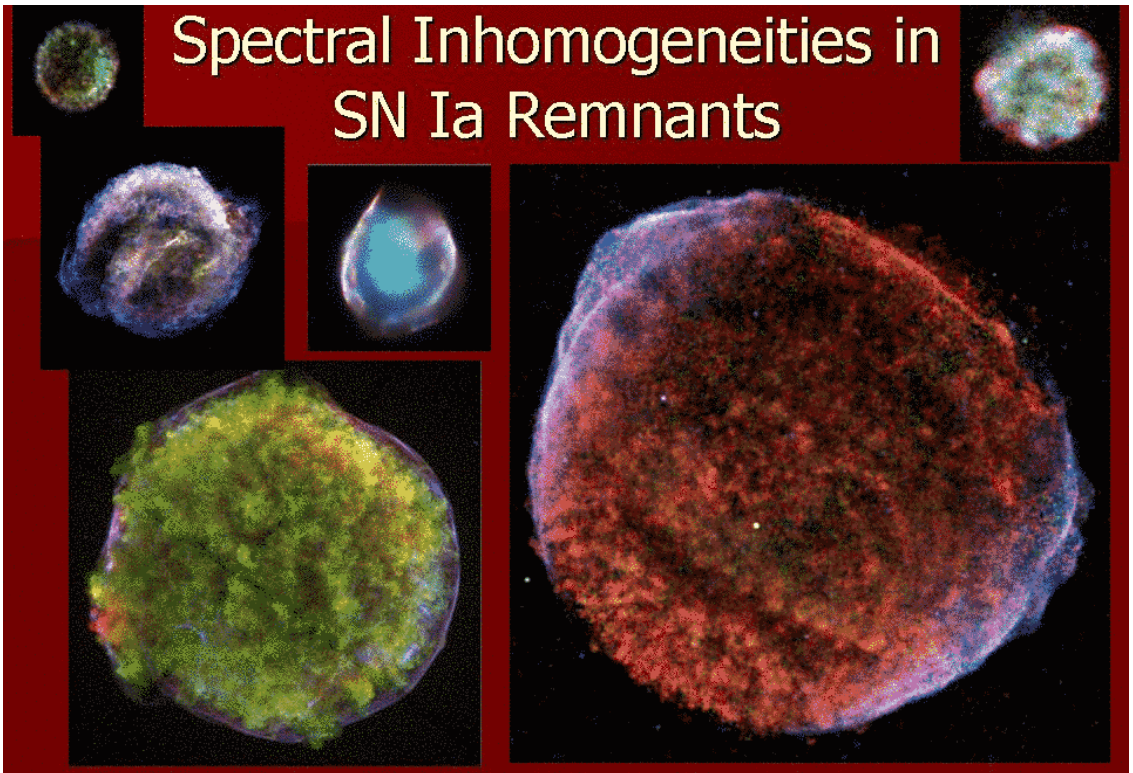
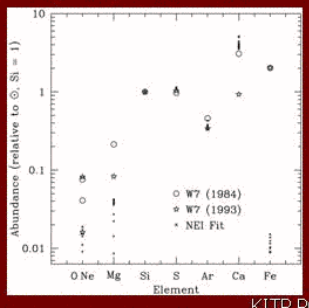
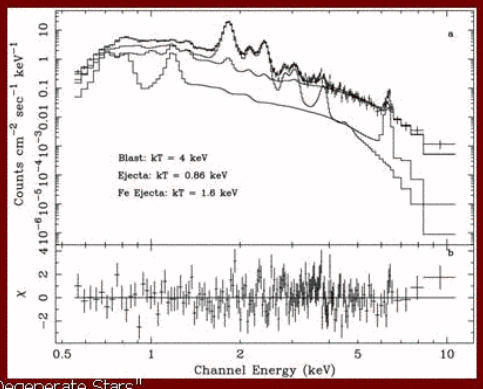
Spectral Inhomogeneities in SN Ia Remnants



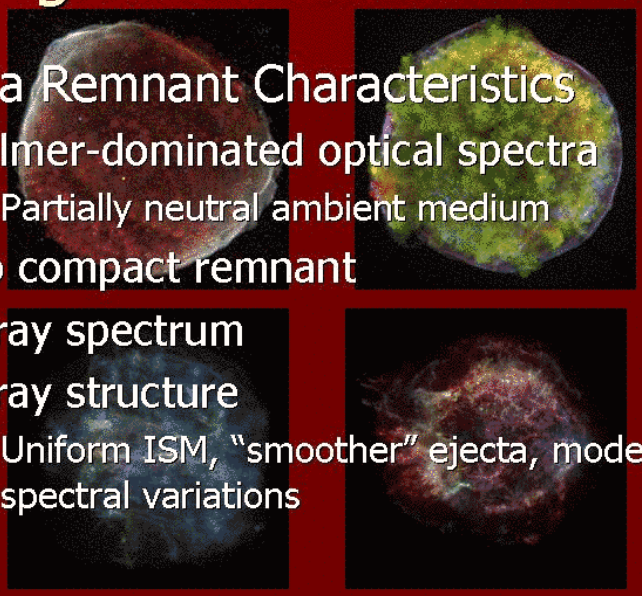
Typing SNe from their Remnants

- SN Ia Remnant Characteristics
  - Balmer-dominated optical spectra
    - Partially neutral ambient medium
  - No compact remnant
  - X-ray spectrum





Typing SNe from their Remnants

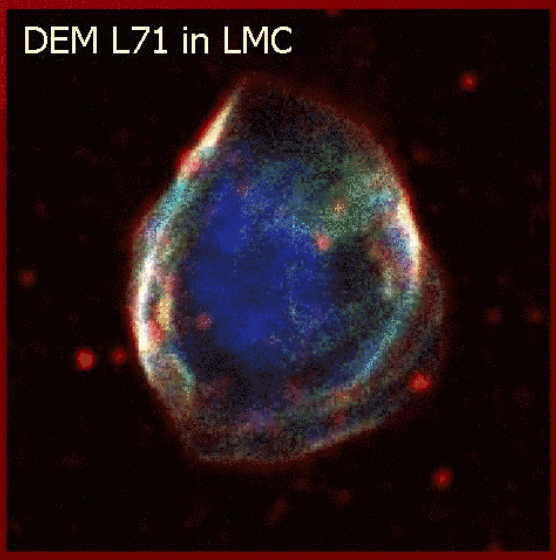


- SN Ia Remnant Characteristics
  - Balmer-dominated optical spectra
    - Partially neutral ambient medium
  - No compact remnant
  - X-ray spectrum
  - X-ray structure
    - Uniform ISM, "smoother" ejecta, modest spectral variations

Typing SNe from their Remnants

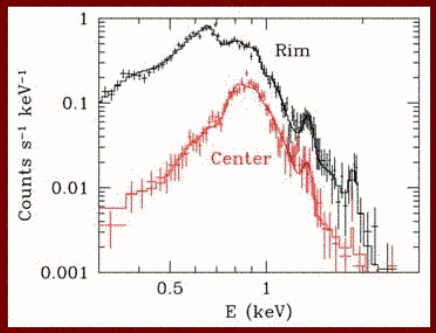
- SN Ia Remnant Characteristics
  - Balmer-dominated optical spectra
    - Partially neutral ambient medium
  - No compact remnant
  - X-ray spectrum
  - X-ray structure
    - Uniform ISM, "smoother" ejecta, modest spectral variations
  - 1.4 solar masses of ejecta
  - Spectroscopy of light echos

Works for Evolved SNRs



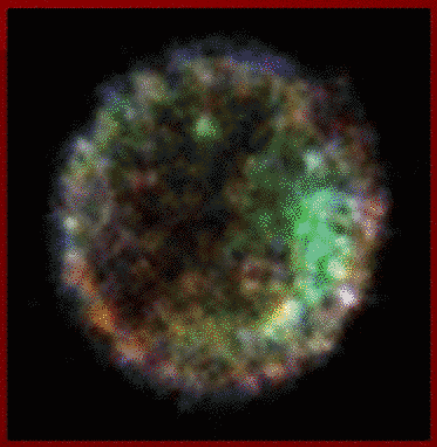
- Middle-aged SNR
  - 36″ (8.7 pc) in radius
  - 4,000 yrs old
- Rims: LMC composition
- Core: [Fe]/[O] > 5 times solar
- Ejecta mass: 1.5 M_{sun}

SN Ia ejecta



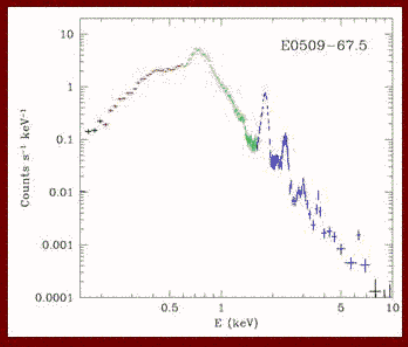
Hughes, Ghavamian, Rakowski, & Slane 2003, ApJ, 582, L95

Young SN Ia Remnant



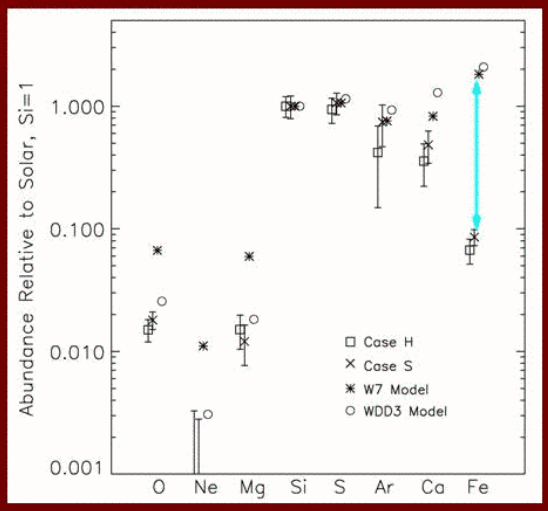
Warren and Hughes 2004, ApJ, 608, 261

- E0509-67.5 in LMC
  - 15″ (3.6 pc) in radius
  - <1,000 yrs old
- Balmer-dominated SNR
- Very round, limb-brightened shell
- Light echo age 400 +/- 150 yrs



E0509-67.5 Spectral Analysis

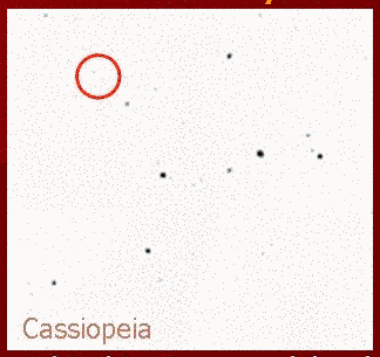
- SN Ia remnant confirmed
  - O, Ne, Mg << Si, S, Ar, Ca
  - Quite similar to global abundance pattern in Tycho (Hwang et al. 1998)
- Preference for specific model
  - Delayed detonation better fit than fast deflagration (W7)
- Other results
  - Low Fe: stratification
  - Age<700 yrs, n_0~0.05 cm^{-3}
  - Continuum mostly nonthermal

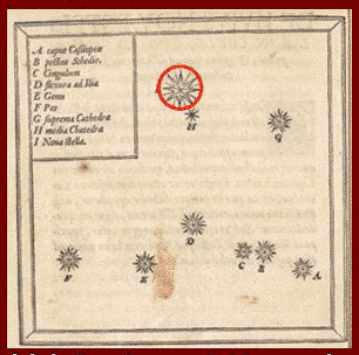


W7: Nomoto et al 1984, Thielemann et al 1993
WDD3: Iwamoto et al 1999
Case H & S (Spectral fit): Warren & Hughes 2004

Tycho Brahe

Discovery of SN 1572



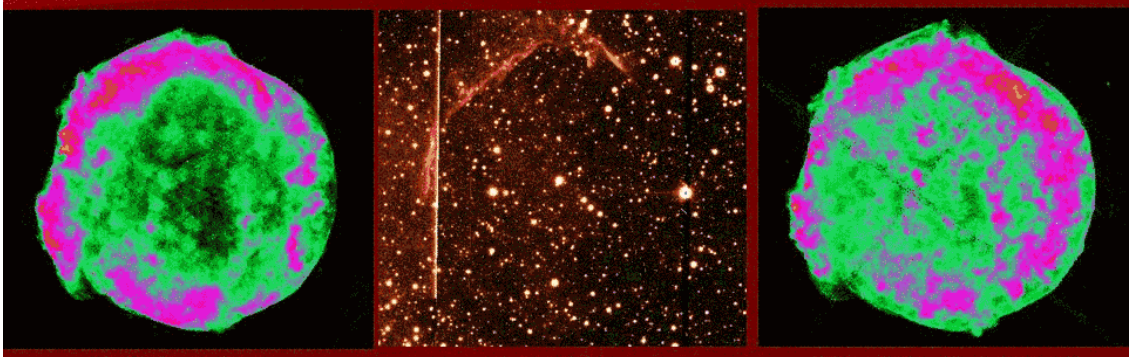


SN 1572 was first sighted in Korea and (probably) Spain on 6 November, then shortly thereafter in China and elsewhere in Europe. It was brighter than Venus (visible at noon for "those gifted with keen sight").

Tycho observed it initially on 11 November (after dinner). He carefully measured its position and brightness until Mar 1574 when it became too faint to see.

The remnant was discovered as a radio source in 1952 (also 3C10), then as a faint set of Hα filaments, and lastly as an X-ray source in 1967. The remnant's center is within ~2′ of Tycho's position.

A Modern View: Tycho's SNR Across Wavebands

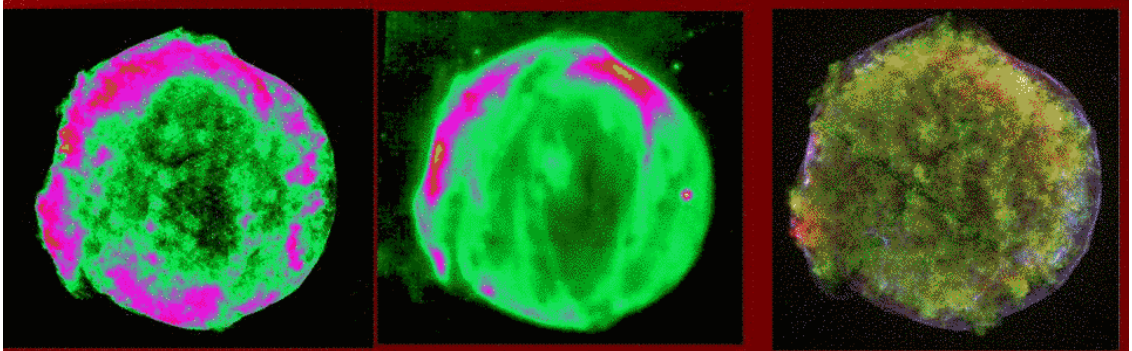


VLA 1.4 GHz | Optical Hα | *Chandra* 0.5-7 keV

Square root scale

Current size ~ 8′ diameter
Only Balmer line optical emission
X-ray spectrum dominated by ejecta

A Modern View: Tycho's SNR Across Wavebands



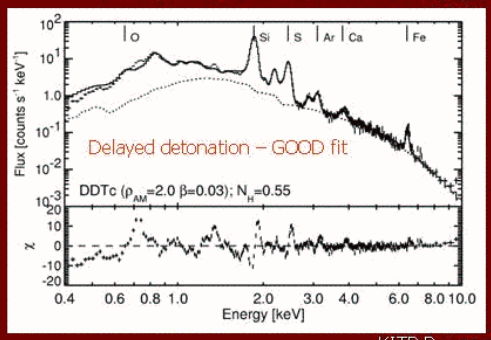
VLA 1.4 GHz | *Spitzer* 24 μm | *Chandra* 0.5-7 keV

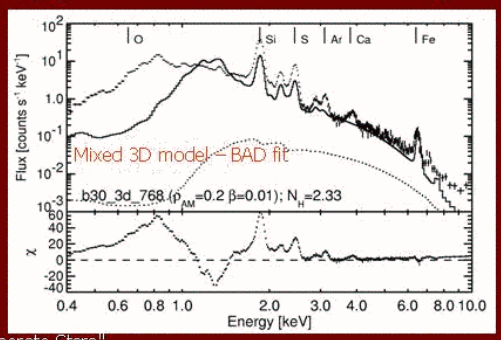
Fe (red), Si (green), 4-6 keV (blue)

Current size ~ 8′ diameter
Only Balmer line optical emission
X-ray spectrum dominated by ejecta

Modeling Tycho, a SN Ia Remnant

- X-ray spectral modeling of SN Ia remnants can constrain explosion mechanism (Badenes et al. 2006)
  - 1D hydro with realistic ejecta models evolved to age of Tycho (430 yrs) in uniform ambient medium
  - Use XMM spectrum from west (spectrally uniform)
  - Only 3 parameters: ρ_{AM}, β, N_H (plus continuum model)





Asymmetries in SN Ia Remnants

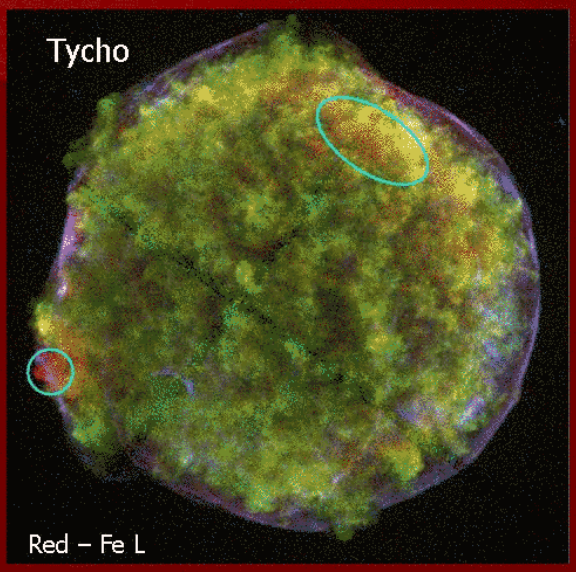
Why this is interesting and useful:

We only have a single sight-line to any individual SN Ia – hence can only constrain models statistically, in the ensemble

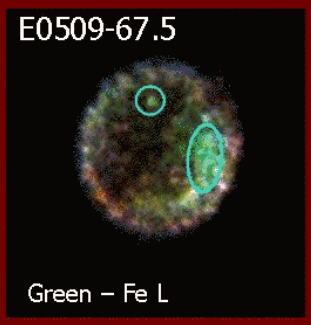
Remnants are optically thin, spread out geometrically, and were the results of successful explosions – light echoes offer potential to confirm Ia origin, and perhaps SN Ia sub-typing

Remnant evolution governed by hydrodynamics, complications include shock physics (electron-ion heating, cosmic ray acceleration), but these are amenable to X-ray observations with many existing observables (e.g., Con-X).

Taking a Higher Resolution View



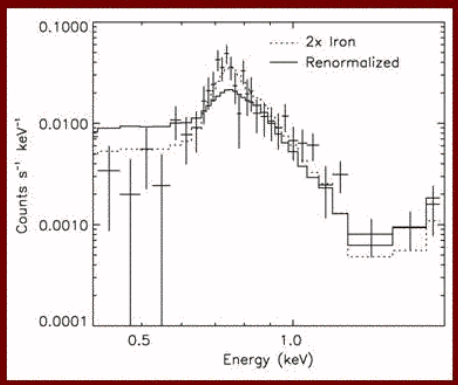
- Ejecta spectral variations
  - Large scale variations in Fe emission properties
  - Isolated clumps



SN Ia Ejecta Clumps

- E0509-67.5 clump: Fe enhanced by factor of ~2, relative to surroundings

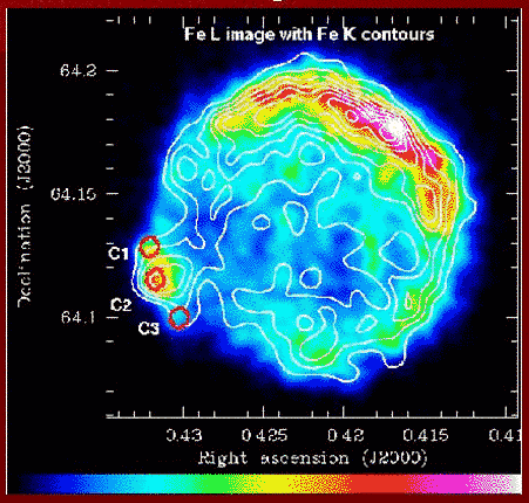
Chandra spectrum of brightest isolated clump in E0509-67.5



Warren & Hughes 2004

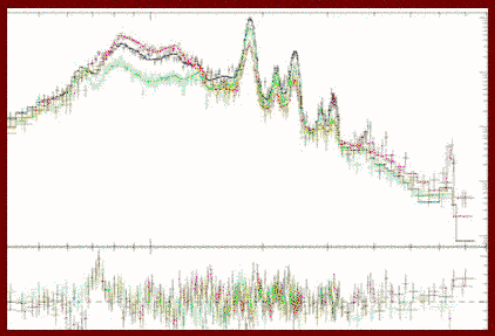
SN Ia Ejecta Clumps

XMM-Newton image



Decourchelle et al. 2001, A&A, 365, L218

- E0509-67.5 clump: Fe enhanced by factor of ~2, relative to surroundings
- Tycho clumps along eastern rim (Vancura et al 1995)
- Varying Si/Fe abundances (XMM)
  - C1: [Si/Fe] ~ 10 (red)
  - C2: [Si/Fe] ~ 3 (black)
  - C3: [Si/Fe] ~ 30 (green)



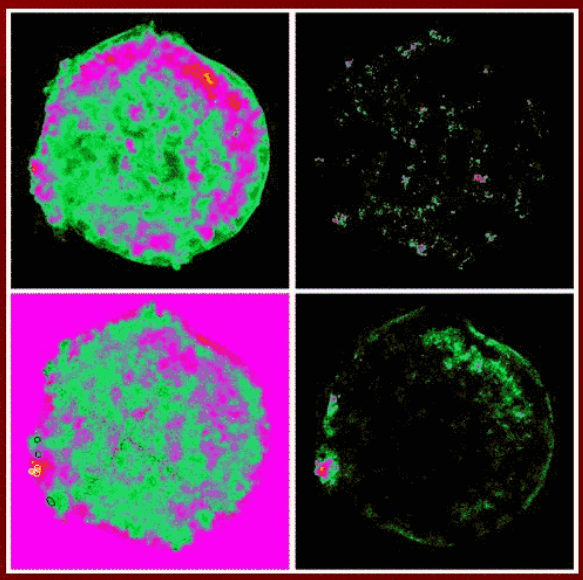
Chandra View of Si/Fe in Tycho

Broadband Chandra image

Examine spectra of six knots at breakout on rim

Si-rich
Fe-rich

1.8 keV (Si) to 0.8 keV (Fe-L) emission ratio



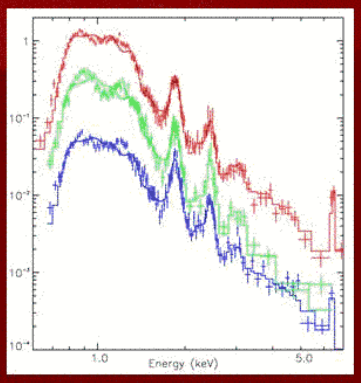
Si-rich emission

"Fe-rich" emission

Hughes et al. 2007, in prep.

Chandra Spectra of Tycho Knots

Fe-rich



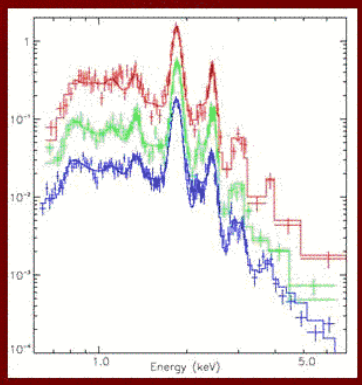
[Si/Fe]

0.32

0.35

0.64

Si-rich



[Si/Fe]

20

15

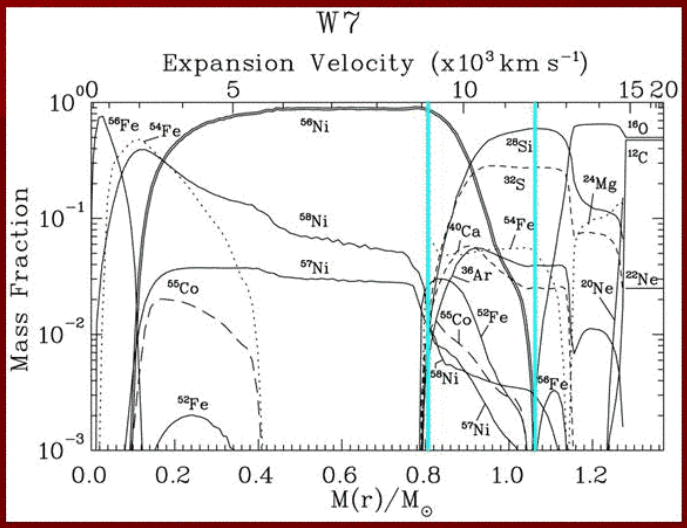
6

Single component fits, kT ~ 3 keV, $n_e t \sim 3 \times 10^{10}$ cm^{-3} s

Si abundances all > 2 x solar (confirmed ejecta knots)

Factor of >60 range in [Si/Fe], but no pure Fe or Si knots

Origin of SN Ia Ejecta Clumps ?



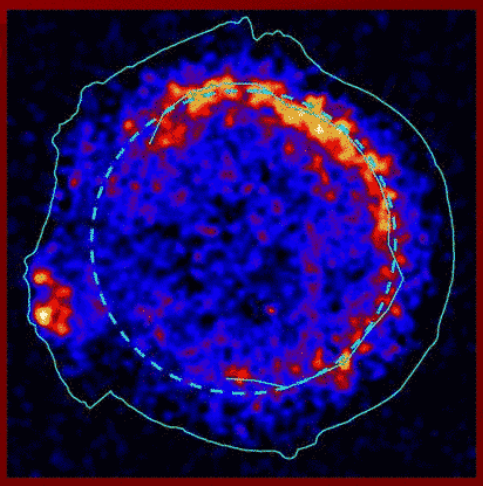
Clumps may originate in the region between Si+S and Fe rich zones

A consequence of the nickel bubble effect?

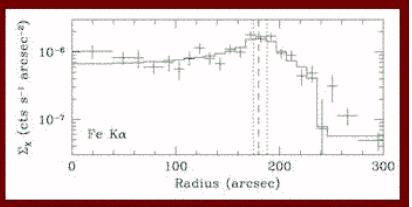
High velocity, asymmetric Ca emission from Ia SNe (e.g., SN2001el)

Chandra View of Fe in Tycho

Fe-K emission at ~6.5 keV (hot Fe, >2 keV)

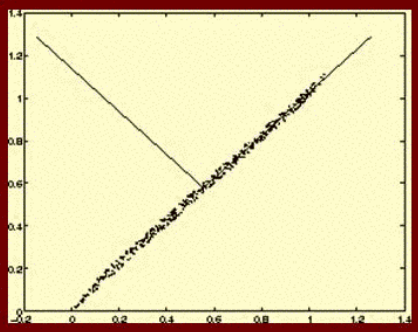


Eastern Fe-rich knots; morphologically distinct from rest of hot Fe (shell-like morphology)



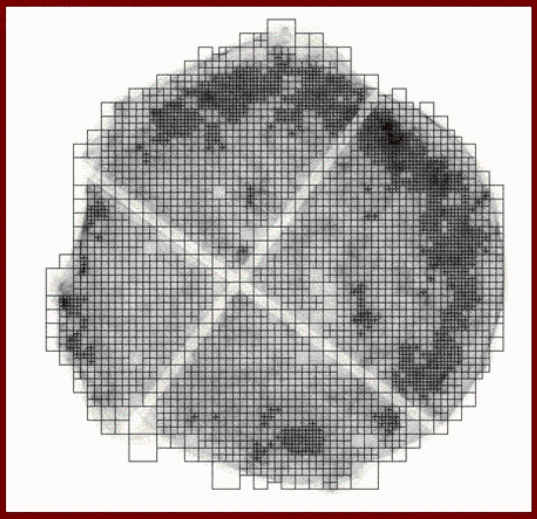
A Digression on Principal Component Analysis (PCA)

- PCA: a classical statistical test
  - Reduce dimensionality of a dataset
  - Identify new underlying meaningful variables
  - Isolate most extreme data points
- Basic idea of PCA
  - Variance maximizing rotation
  - New axes are orthogonal
  - Precondition data points – center and standardize
  - Eigenvalue problem



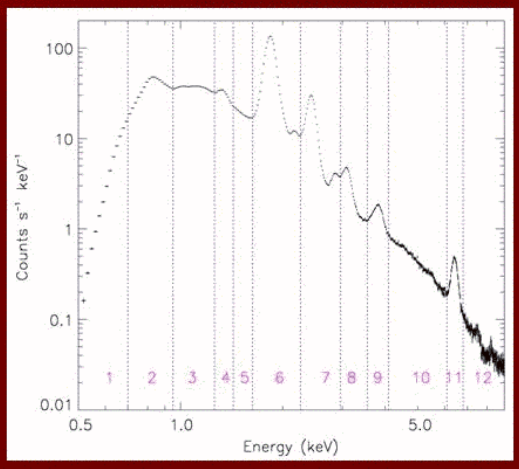
Application to *Chandra* Data - I

- Tycho
  - Observed early 2003
  - 150 ks
  - Centered on ACIS-I
- Image binning
  - Adaptive mesh: ensure 1000 X-ray events per region
  - Extract 4479 spectra



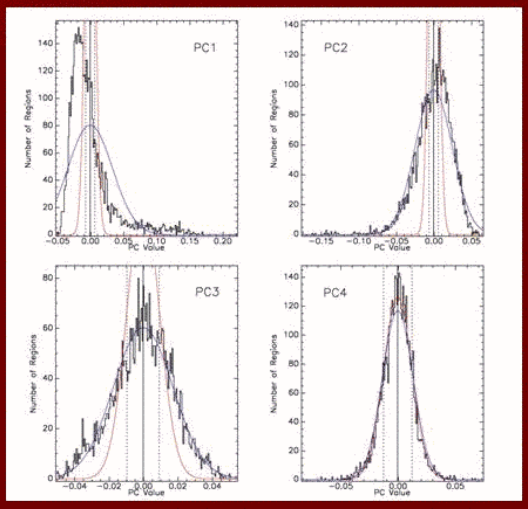
Application to *Chandra* Data - II

- Spectral binning
  - Group channels into 12 broad bands
  - Isolate interesting spectral features, e.g.
    - 2,3: Fe-L
    - 4: Mg-K
    - 6: Si-K
    - 10: 4-6 keV cont.
    - 11: Fe-K

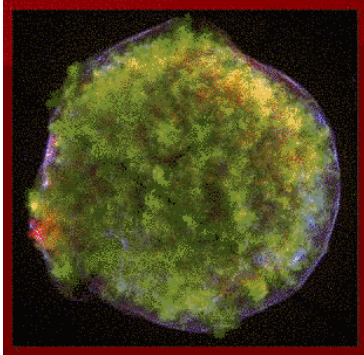


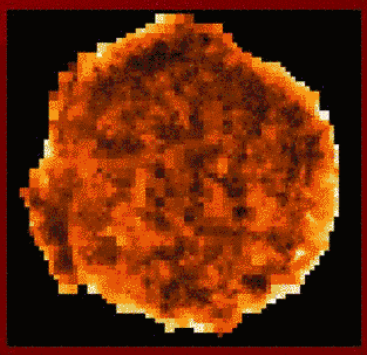
Results of PCA

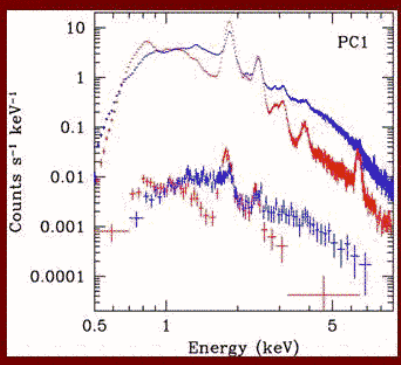
- Simple-minded picture: PCA is similar to a generalized hardness ratio
- 3 PC's explain 77% of the variation in Tycho
  - Project all 4479 spectra onto new axes (PC) and plot distributions
- Most points localized in one big group
  - Tails off to one side in both PC1 and PC2 axes



First Principal Component







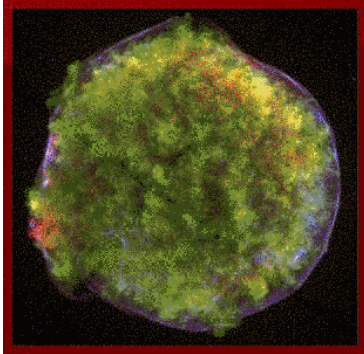
Extreme spectra

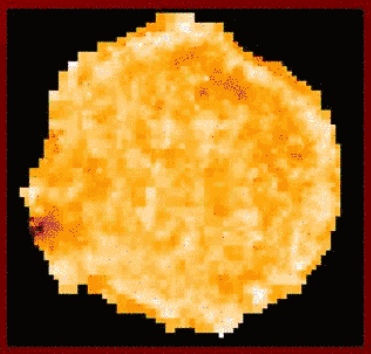
Accounts for 43% of total spectral variation

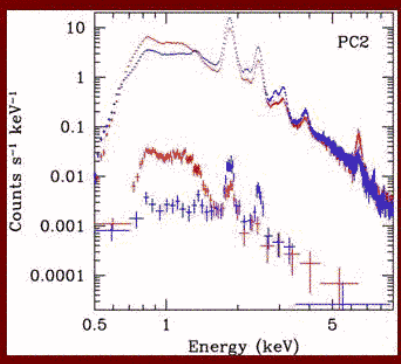
Spectra vary from line-dominated (interior) to featureless (rim)

Warren, Hughes, Badenes, et al. 2005, ApJ, 634, 376

Second Principal Component







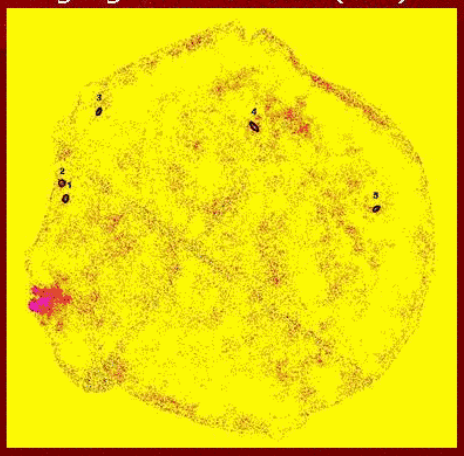
Extreme spectra

Accounts for 23% of total spectral variation

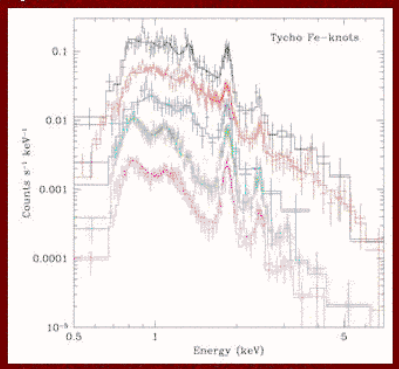
Spectra vary from Fe-rich (e.g., eastern blob) to Si-rich

Comprehensive View of Fe Emission in Tycho

Highlight Fe emission (PC2)



Spectra of other Fe-rich knots



[Si/Fe]
1.16
0.96
1.40
2.55
2.90

Eastern Fe-rich knots:

- Morphologically distinct
  - only Fe-rich knots at rim
- Spectrally distinct
  - most Fe-rich across entire SNR

SN Ia Explosion Models

As an accreting CO white dwarf approaches the Chandrasekhar mass, it begins to "smolder"

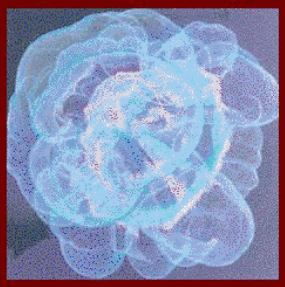
Ignition of the thermonuclear flame occurs near the star's center

The resulting hot bubble of Fe-rich "ash" is buoyant

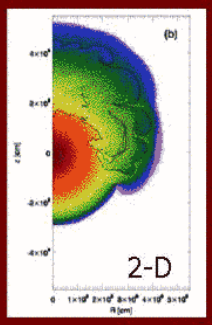
Not yet clear how many such bubbles are involved, but the process is essentially multi-dimensional

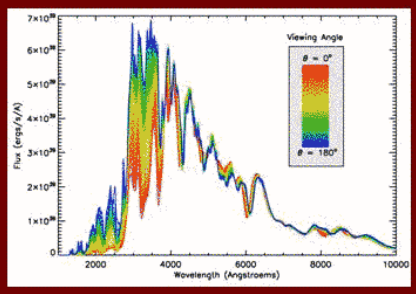
Some SN Ia (e.g., SN2001el) show high velocity, asymmetric Ca emission

Optical spectro-polarimetry also indicates significant asymmetry



Simulation of a buoyant bubble being sheared by Rayleigh-Taylor instabilities (from Flash Center at Chicago)





Kasen & Plewa (2007), astro-ph/0612198

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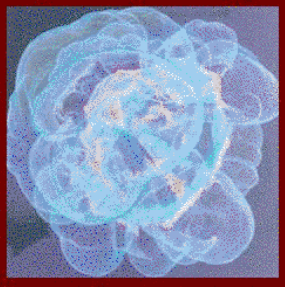
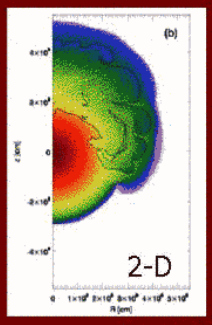
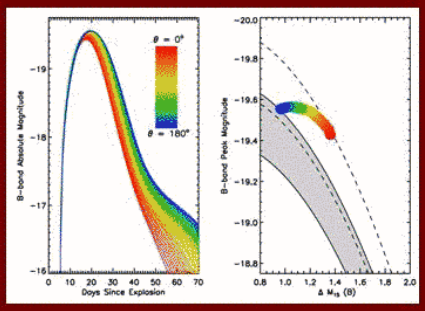


Simulation of a buoyant bubble being sheared by Rayleigh-Taylor instabilities (from Flash Center at Chicago)





Kasen & Plewa (2007), astro-ph/0612198

SN Ia Explosion Models

As an accreting CO white dwarf approaches the Chandrasekhar mass, it begins to "smolder"

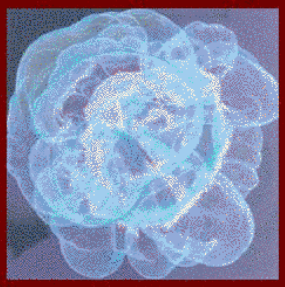
Ignition of the thermonuclear flame occurs near the star's center

The resulting hot bubble of Fe-rich "ash" is buoyant

Not yet clear how many such bubbles are involved, but the process is essentially multi-dimensional

Some SN Ia (e.g., SN2001el) show high velocity, asymmetric Ca emission

Optical spectro-polarimetry also indicates significant asymmetry



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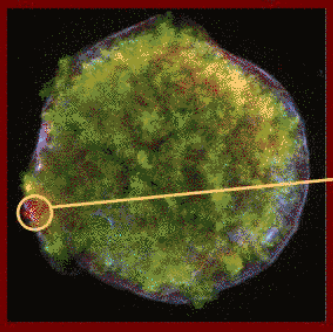
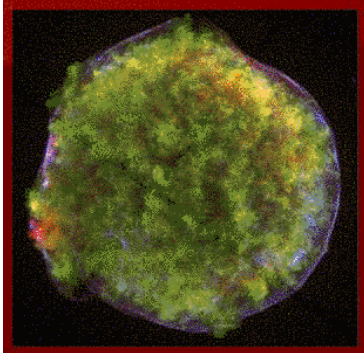
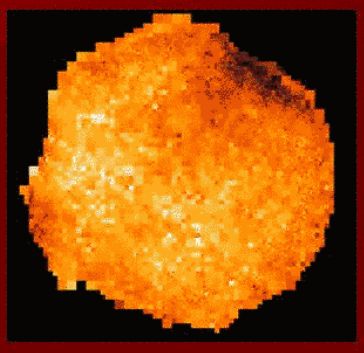
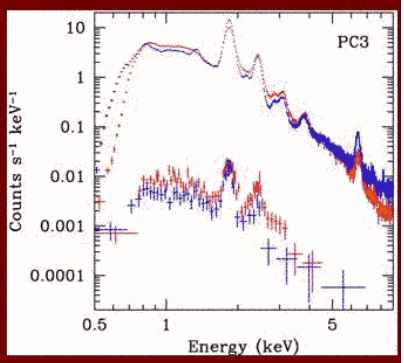


Is this a spark from the ignition of the SN Ia explosion that formed the Tycho SNR?

Third Principal Component







Extreme spectra

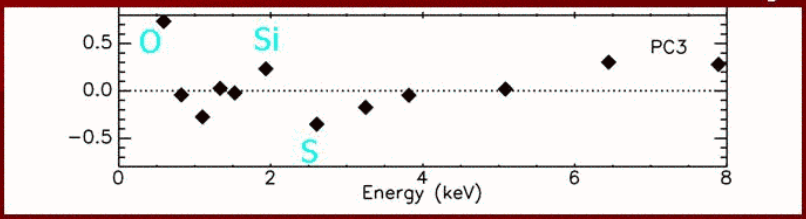
Accounts for 11% of total spectral variation

Spectra contain less (rim, west) or more (interior, east) emission below 0.7 keV

Entirely new spectral component!

Interpretation of PC3

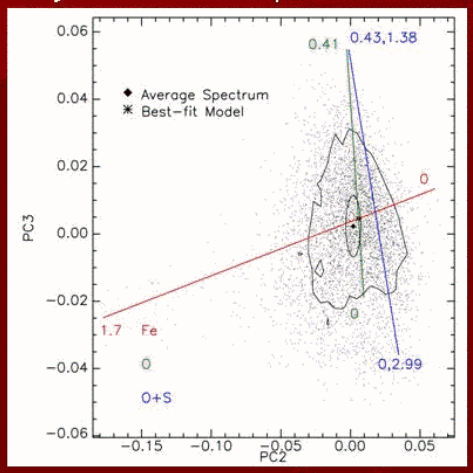
Eigenvector spectrum



- Lowest energy bin: variation in ISM absorbing column?
  - Expect higher N_H toward NE near HI cloud
  - Requires N_H to vary by factor of 2 for PC3 spectral range – not consistent with N_H measurements from rim
- Additional soft (kT ~ 0.3 keV) component
  - Cannot explain full PC3 range (both excess and deficit in first bin)
- Abundance variations
  - Oxygen emission in 1st bin anti-correlated with Sulfur emission in 7th bin

Interpretation of PC3

Projections onto PC2-PC3 plane

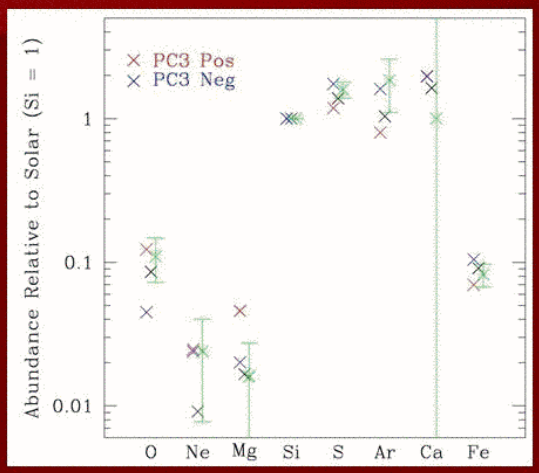


Abundance variations

- Red line
  - Vary Fe abundance alone in best fit model to average spectrum
  - "Track" goes in wrong direction to explain PC3 and does not get to full range
- Green line
  - Vary O abundance
  - Does not get to low enough values of PC3
- Blue line
  - Allow O and S abundances to vary (anti-correlated)
  - Can explain full range of PC3

Interpretation of PC3

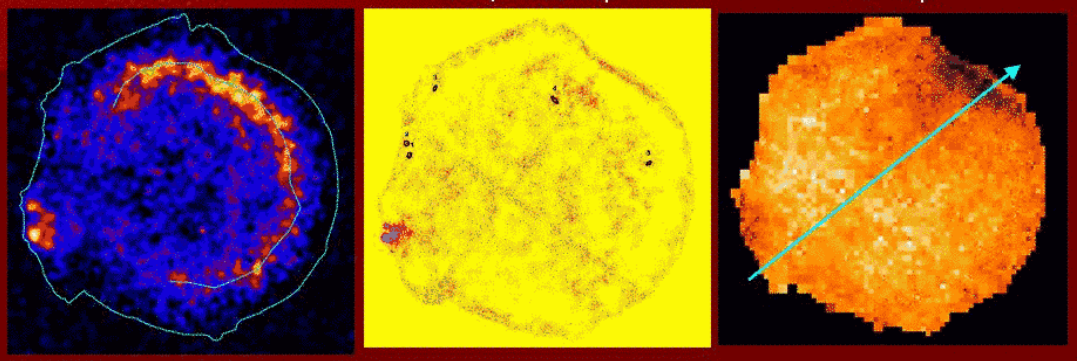
Abundances from XMM-Newton Spectral Fits



- Red points
  - Spectra extracted from regions with large positive values of PC3
- Blue points
  - Large negative values of PC3
- Results
  - Abundance ratios:
  - O 0.47
  - S 1.5
  - Fe 1.6

Tycho Summary

Fe-K emission | Fe-L/Si ratio map | PC3 map



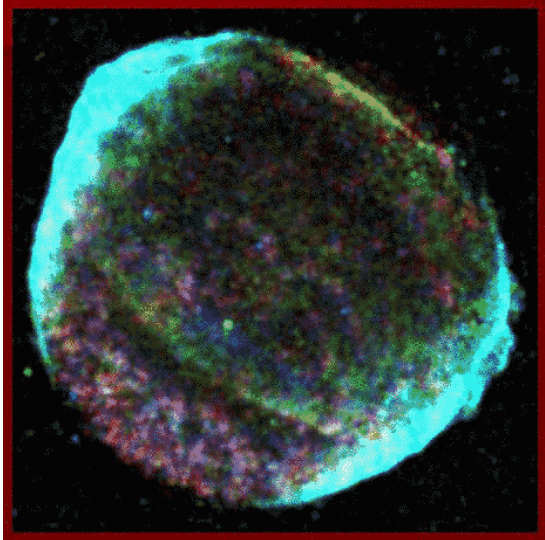
Fe-rich knots

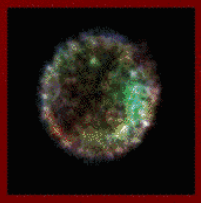
- Morphologically distinct
- Spectrally distinct
- Mass ~ 3 x 10^{-4} M_{sun}

PC3 composition variation

- O-abun decreases, S-abun increases in direction of arrow
- Ejecta or ISM interaction?

Other SN Ia Remants?

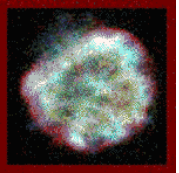


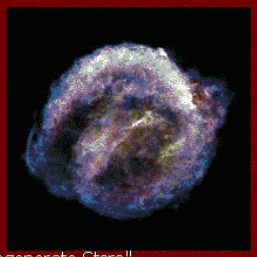


E0509-67.5
Fe-rich blob ("eye")
Mass ~ 6 x 10^{-4} M_{sun}

SN1006
O (red), Ne (green), Si (blue)
Very little hot Fe – no obvious blobs

E0519-69.0





Kepler