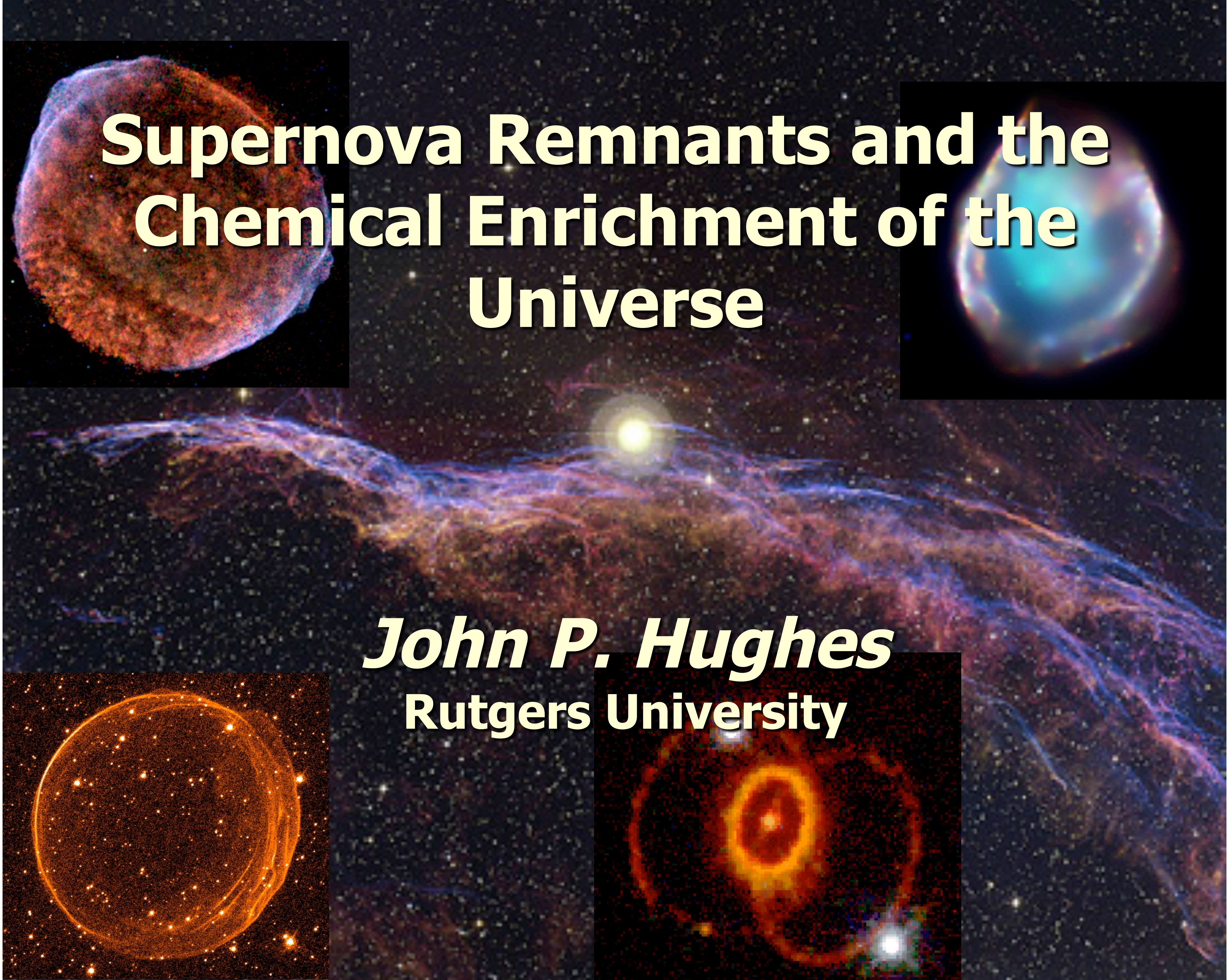
Supernova Remnants and the Chemical Enrichment of the Universe



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White Paper based on AAS Poster

Supernovae and Supernova Remnants in the IXO Era

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Pat Slane (SAO)
Alicia Soderberg (Harvard)
and Con-X SNR panel

Discussions here with Jacco Vink and others. Contact me if you want to contribute or help review.

Key Topic

Nucleosynthesis and Explosion Mechanisms in Supernovae through Studies of Supernova Remnants

Core Collapse (CC) SNe

- ~ 3/4 of all SNe
- M(progenitor) > 8 solar masses
- Predominant producers of O, Ne, Mg
- Leave compact remnants
- Gaseous remnants highly structured and asymmetric
- Precise explosion mechanism unknown

Thermonuclear SNe

- ~ 1/4 of all SNe
- White dwarfs that grow to near the Chandrasehkar mass
- Predominant producers of Fe
- Gaseous remnants relatively symmetric
- Progenitor systems and precise explosion mechanism unknown

Key Topic

Nucleosynthesis and Explosion Mechanisms in Supernovae through Studies of Supernova Remnants

Why X-rays?

- Uniquely illuminate the composition and dynamics of the shocked ejecta and ambient medium – no other wave band offers as comprehensive a view
- SNRs offer a 3-D view of the entire ejecta – impossible to obtain on any individual SN, for which we sample a single line-of-sight

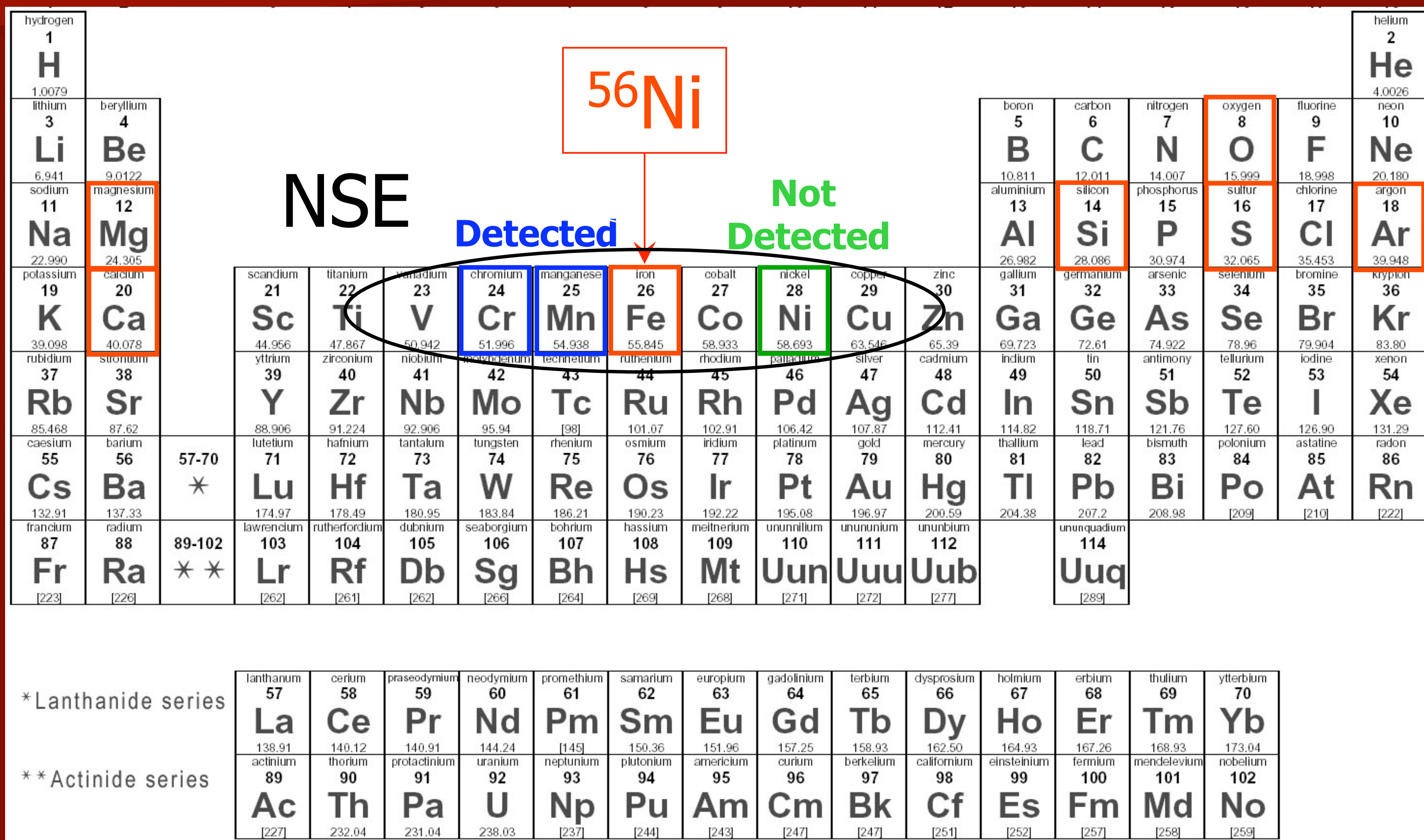
Fe-group synthesis

- CC SNe – Fe comes from the innermost parts of the exploding star; it is closest to the process (jet, neutrino-driven convection) that drives the explosion
- In SN Ia, nucleosynthesis **is** the explosion (provides the energy to unbind the star); amount of Fe is key to optical light curve
- Fe is seen in galaxy clusters to cosmological distances

Fe-group Elements

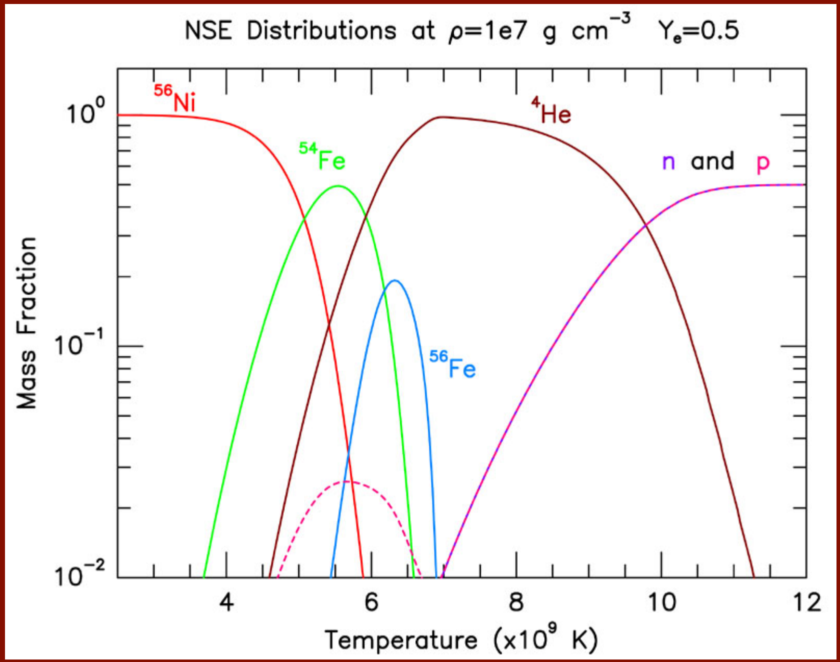
In SNe Ia C-O burns at high P and T to nuclear statistical equilibrium (NSE)

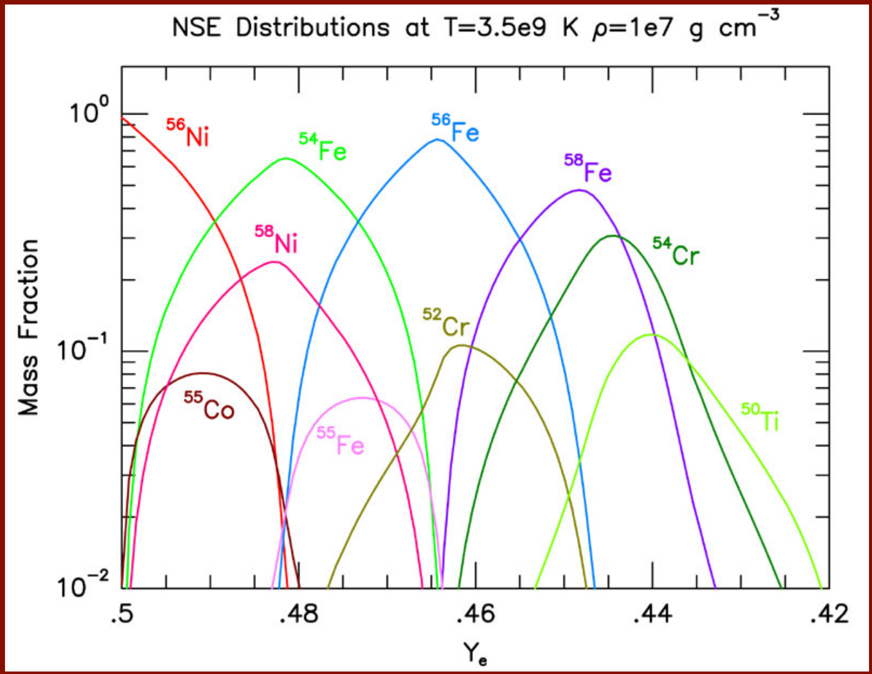
In CC SNe, Fe-group elements form explosively at temperatures of 4-5x10^9 K



NSE

Nucleosynthesis in nuclear statistical equilibrium (NSE) depends on temperature, density, and Y_e (neutron excess)



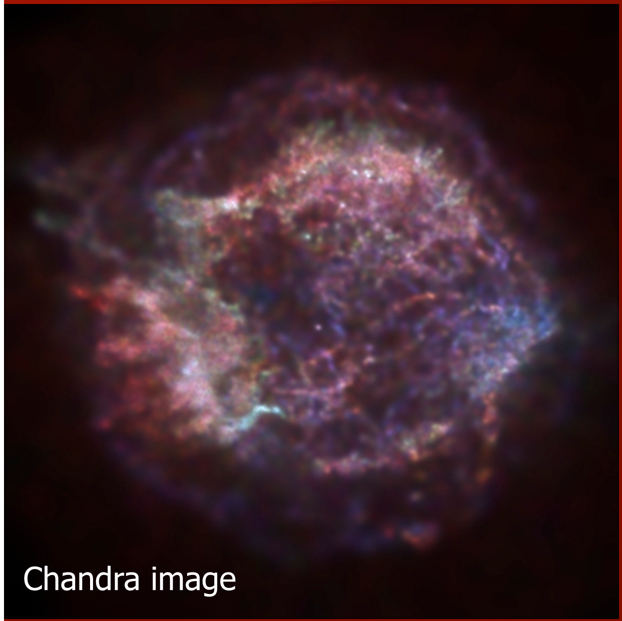


From Frank Timmes

Increasing neutron excess

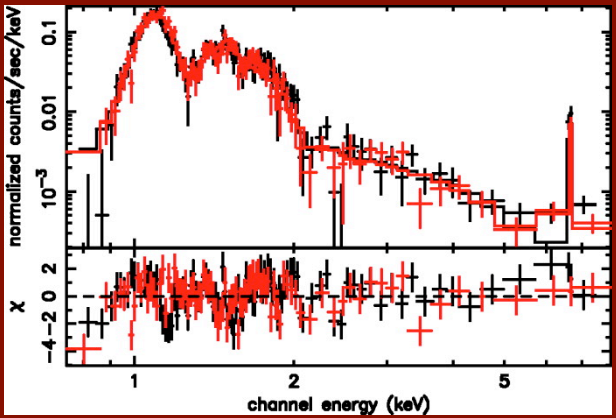
CC SN Example

Cassiopeia A



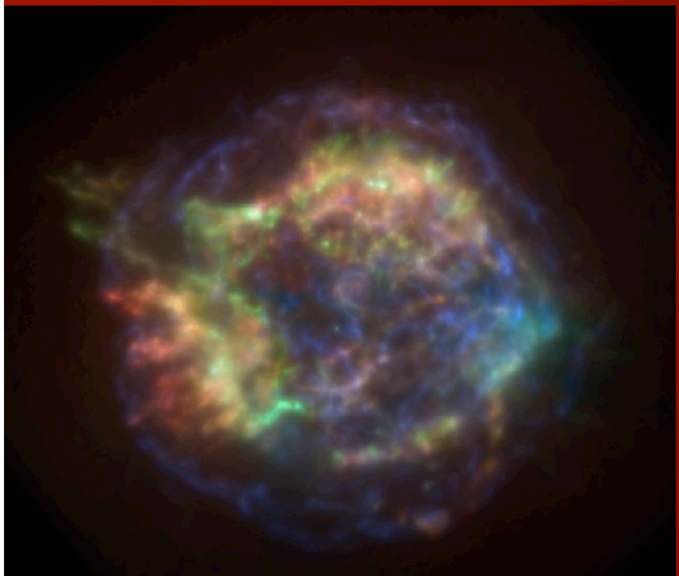
Current Results

- Spatial distribution of main nucleosynthetic products (Fe, Si, O) vary widely in reverse-shock heated ejecta
- Large bulk velocities (±2000 km/s) present
- Nearly pure-Fe knots found (from "α-rich" freeze-out or explosive complete Si-burning)



CC SN Example

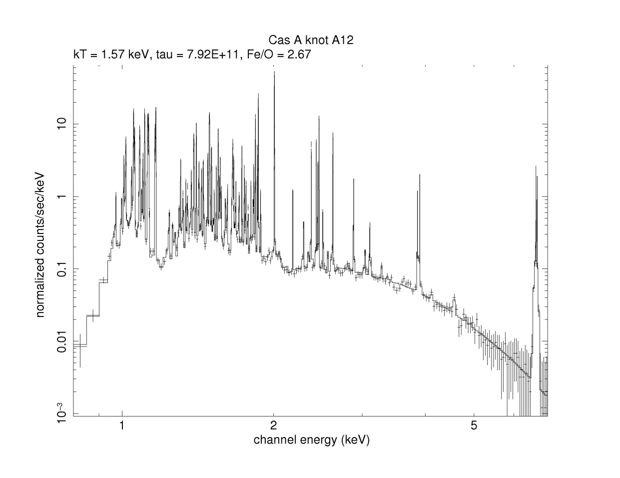
Cassiopeia A



Chandra image convolved with IXO beam

IXO Advances

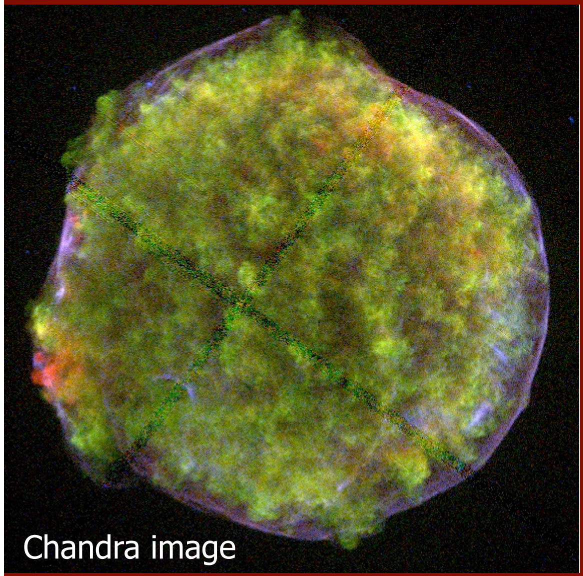
- IXO with 5” beam will resolve many individual spectrally-distinct knots
- Fe knots yield rich, highly-sampled spectra for measurement of Cr, Mn, Ni, Fe, relative abundances
- Expect count rate of ~0.25 IXO counts/s from innershell K lines of ^{44}Sc and ^{44}Ca from ^{44}Ti decay



Complete census (mapping and dynamics) of ^{44}Ti production

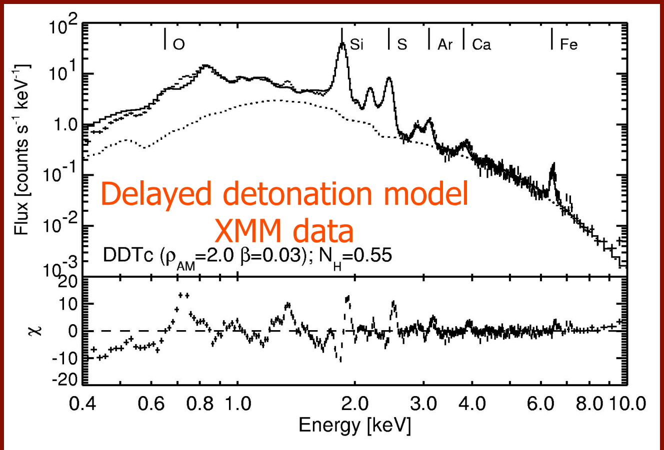
SNIa Example

Tycho Supernova Remnant



Current Results

- Type Ia nature recently confirmed through light echo spectroscopy (Rest et al. 2008; Krause et al. 2008) – looks like a "standard" SN Ia.
- X-ray spectra of Tycho also consistent with "standard" SN Ia explosion model (Badenes et al. 2006)

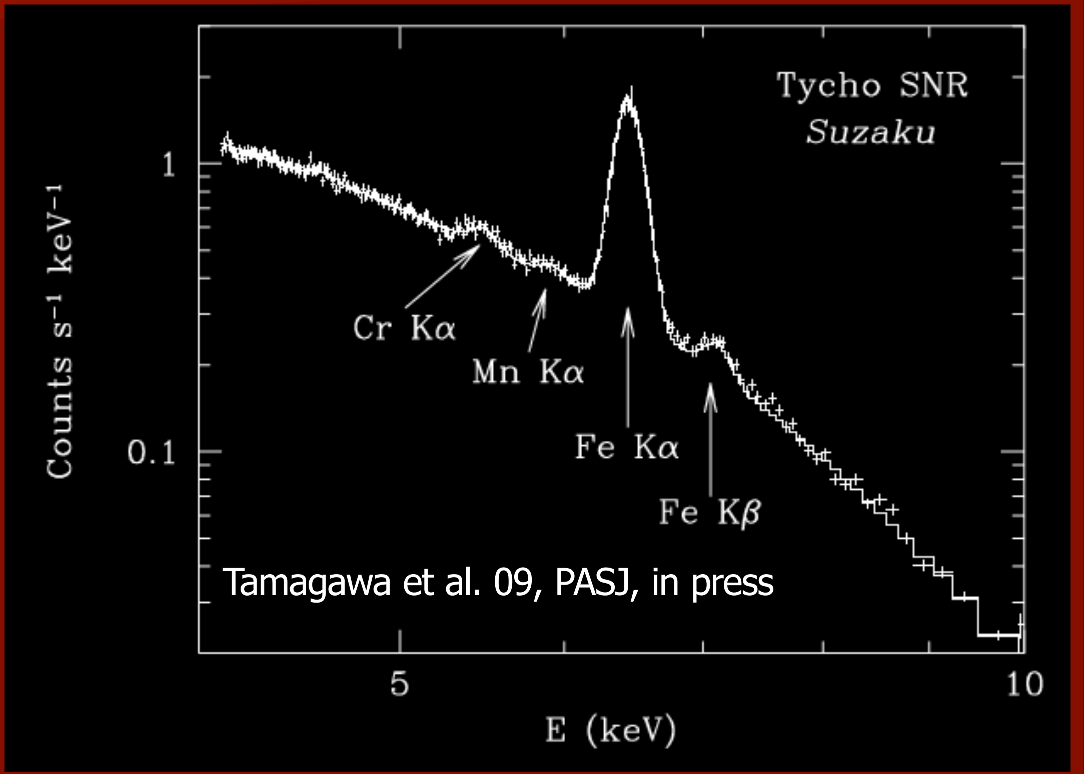


Suzaku integrated spectrum of Tycho

Suzaku detection of secondary peak Fe-group elements:

Cr (>10σ) and Mn (>7σ) Kα emission lines from Tycho SNR ejecta

Mn/Cr mass ratio in SNIa explosions is a strong function of the progenitor's metallicity (Badenes, Bravo, & Hughes 2008)



Mn/Cr as a Metallicity Tracer

- Metallicity is an important constraint on the age of a progenitor system.

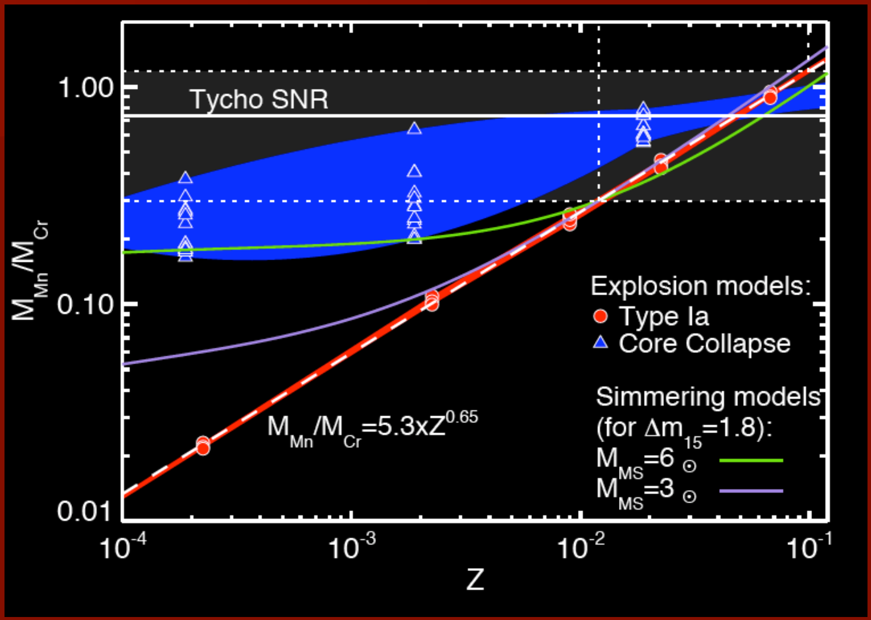
Processes during the Progenitor's Evolution:

- During the progenitor's MS hydrogen burning through the CNO cycle an excess abundance of ^{14}N develops
- This gets converted to ^{22}Ne during hydrostatic He-burning, which increases the neutron excess of the WD material
- Timmes et al. (2003) have shown that there is a linear relationship between the neutron excess and the original metallicity of the progenitor
- The neutron excess determines the relative proportion of Fe-group elements produced at NSE.

Mn/Cr as a Metallicity Tracer

Processes during the SN explosion

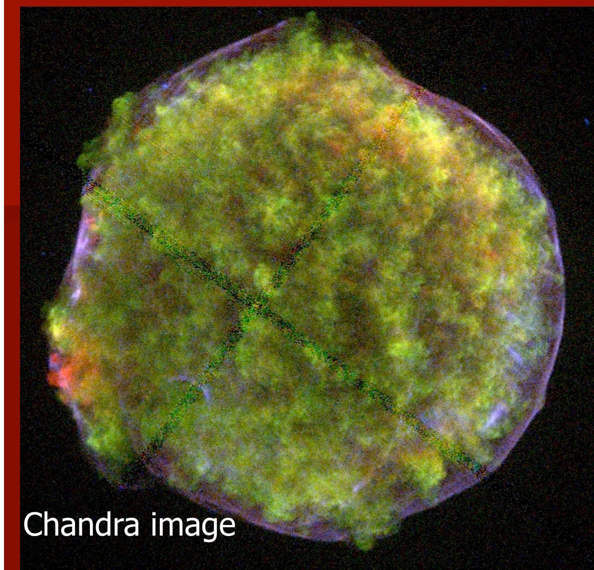
- Model SNIa explosions using different neutron excesses and various classes of explosions (delayed detonations, etc.)
- Complexities due to gravitational settling of elements and pre-explosion simmering of WD
- For the progenitor of Tycho's SN, this yields a supersolar metallicity
  - Z = 0.048 (-0.036, + 0.051)
  - Large uncertainty, but definitely not subsolar

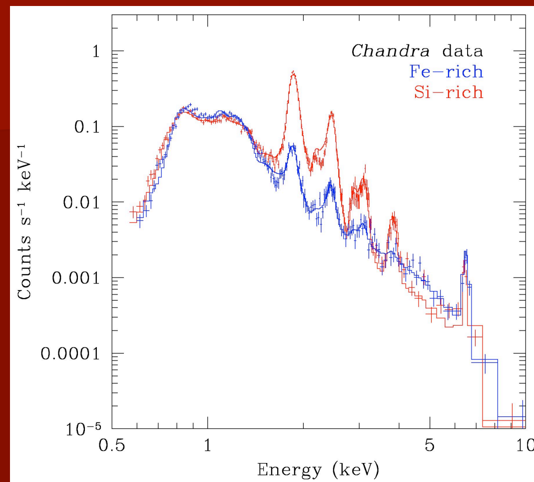


Badenes, Bravo, & JPH 2008, ApJL, 680, L33

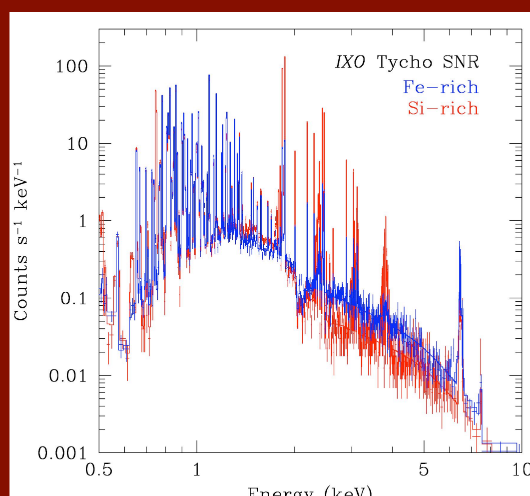
- Mn/Cr also detected in W49B, while Cr is seen in Kepler and Cas A. IXO should allow detection in ~20 Galactic or Magellanic Cloud SNRs

IXO Simulations


Chandra image




Chandra image convolved with IXO beam



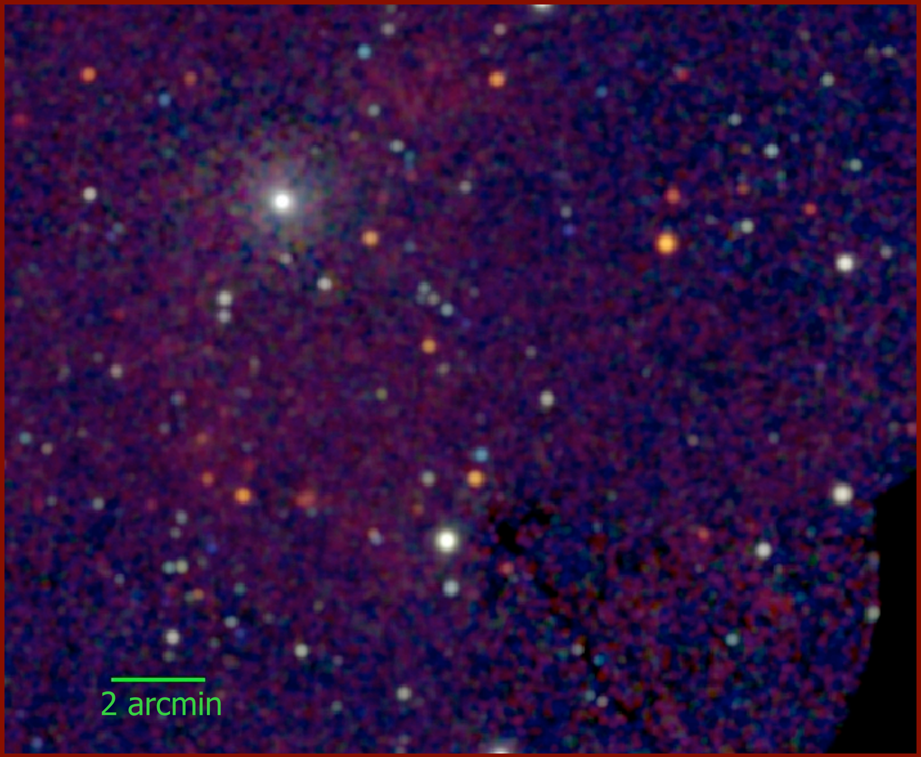
IXO can detect the Mn and Cr Kα lines in Tycho on spatial scales of 15″ in exposures of 200 ks or less. (How did the Fe-rich knots on eastern limb form?)

IXO will map the spatial distribution of Fe-group trace elements in ~10 remnants of SN Ia's

SNRs in M33

ChASeM33 – Plucinsky, et al. Cycle 7 VLP

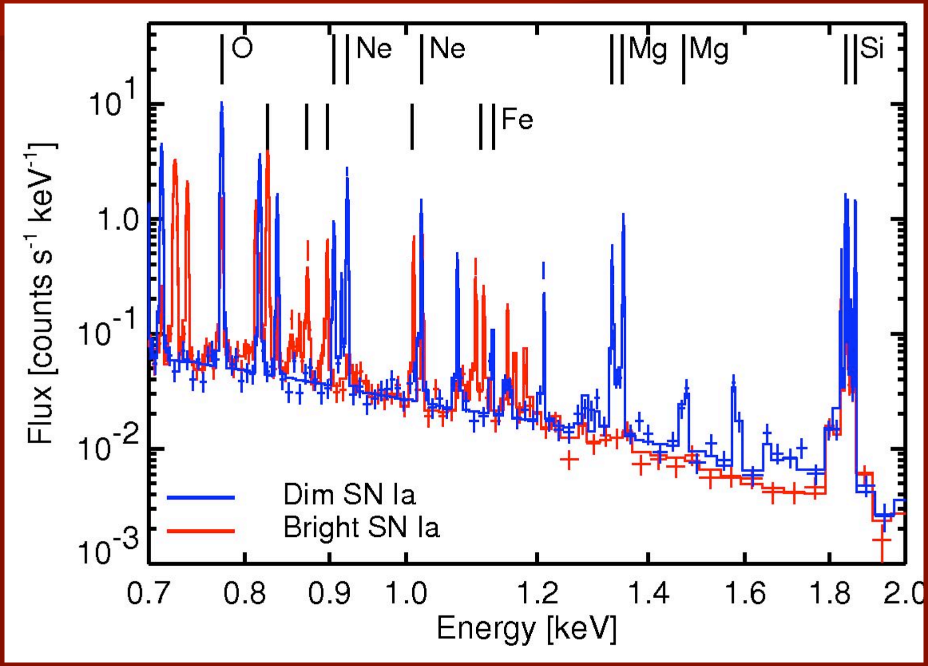
- Seven 200 ks Chandra pointings, covering the central portion
- D = 817 kpc
- ~100 optically discovered SNRs, 30 – 40 with X-rays



This image plots the deep Chandra images of M33 (Plucinsky et al. 2008) convolved with *IXO*'s PSF, showing that most X-ray sources are cleanly resolved. M33 and M31 will be fertile ground for X-ray spectral studies of many source populations, especially SNRs.

Remnants of SN Ia in M33?

An example science project, once young SN Ia remnants are found in M33:



There is growing evidence that bright and dim Type Ia SNe have different progenitors (Scannapieco & Bildsten 2005). X-ray spectra of the remnants can distinguish between SN Ia subtypes (Badenes at al. 2006, 2008). *IXO* simulations (left) show obvious differences between bright (Fe-rich) subtypes (red curve) and dim (Fe-poor) ones (blue) in 100 ks long observations of 400-yr old SNRs.

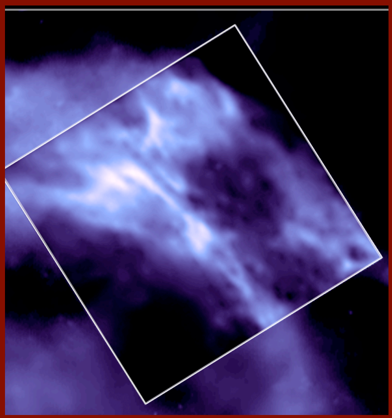
IXO will allow a statistical study of SN Ia progenitor properties in relation to stellar populations in M33 (and M31).

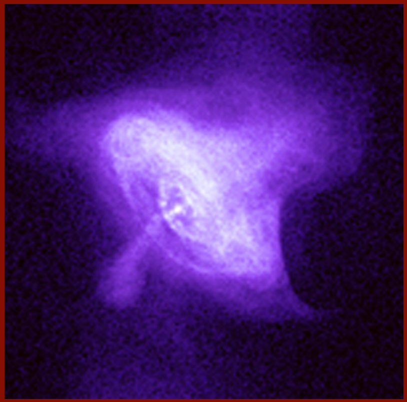
Other Topics

X-ray Polarization

SNRs like RXJ 1713.7-3946 (below left) and pulsar wind nebulae like the Crab Nebula (below right) are dominated by nonthermal synchrotron X-ray emission and therefore are prime targets for X-ray polarization studies.

By examining how the polarization fraction varies across the shock in RXJ 1713.7-3946 we may be able to test whether the amplified magnetic field (turbulent) decays away post-shock (Pohl et al. 2005). The polarization fraction as a function of energy may help identify the thermal emission.





Other Topics

Early time emission from SNe

Basic Questions

- What is the ambient medium density around Type Ia SNe? Depends on model assumptions (Te to Ti ratio); needs earliest possible response time
- Lots can be done on specific CC SNe types (a number already detected by Einstein Obs, ROSAT, Chandra, XMM)
- Also recover X-rays from decades-old SNe
- Entire topic needs to be studied more

Other Topics

The Physics of Shocks

Basic Questions

- Temperatures of electrons vs ions.
  - IXO will do this for many SNRs, but there are only very few cases where proton temperature can be measured
- Nonthermal X-ray emission
  - Thin rims in Tycho, Cas A, Kepler, etc. need Chandra resolution (or better!)
  - Broadband X-ray spectra integrated over the entire radial extent of rim useful to define electron spectrum and synchrotron cooling in conjunction with TeV γ-rays