X-ray Studies of Supernova Remnants

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Supernova Explosions

Ia Thermonuclear Runaway

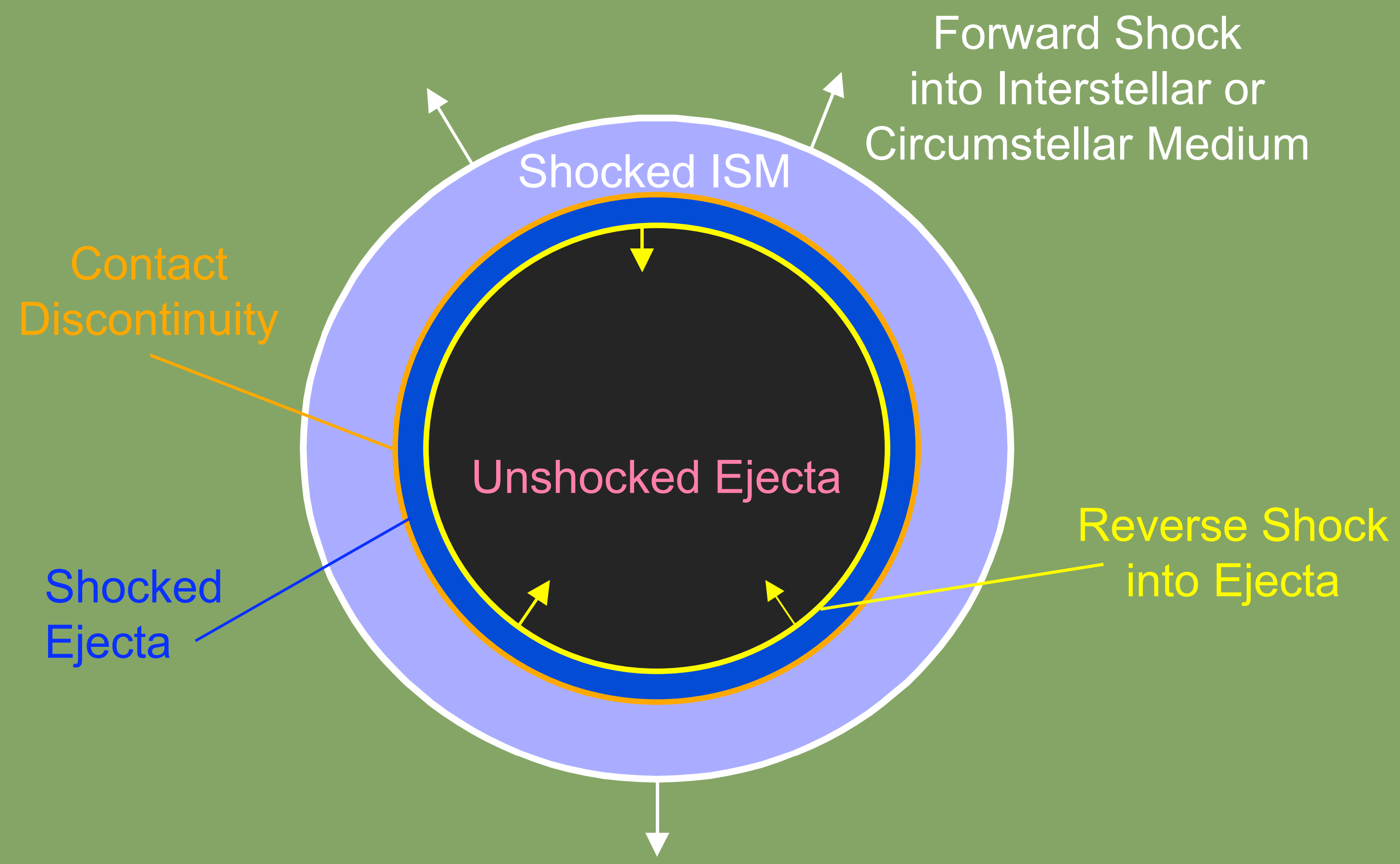
- Accreting C-O white dwarf reaches Chandrasekhar mass limit, undergoes thermonuclear runaway
- Results in total disruption of progenitor ⇣
- Explosive synthesis of Fe-group plus some intermediate mass elements (e.g., Si)
- Uncertain mechanism and progenitor: probably a delayed detonation (flame transitions from subsonic to supersonic speed)

II/Ib/Ic Core-Collapse of Massive Progenitor

- Massive progenitor core forms neutron star or black hole
- Explosive nucleosynthesis products near core (Si and Fe) plus hydrostatically formed outer layers (O, Ne) are expelled
- Most of the explosion energy is carried away by neutrinos
- Uncertain mechanism details involve neutrinos, probably large-scale shock instabilities, rotation, possibly magnetic fields

Supernovae and their progenitors provide most of the heavy elements in the Universe and deposit kinetic energy (10^{51} ergs each) into the interstellar medium

Supernova Remnant Cartoon



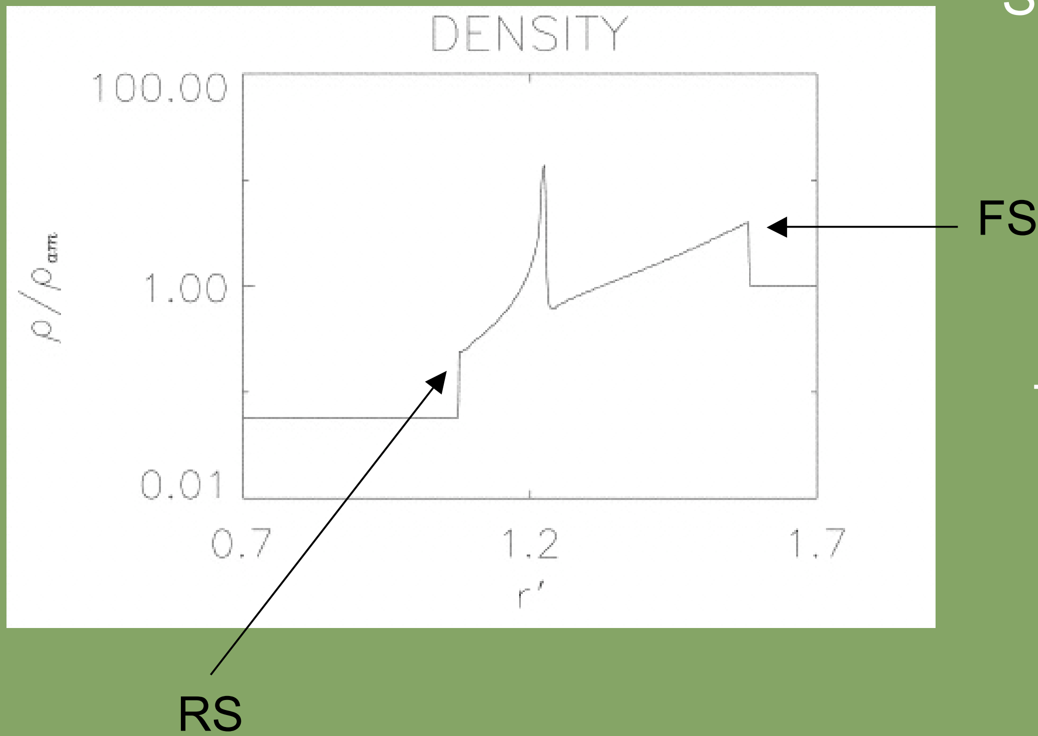
Forward shock moves supersonically into interstellar/circumstellar medium
Reverse shock propagates into ejecta, starting from outside

Remnant Evolution

Free Expansion
Ejecta expand without deceleration r~t

Adiabatic (Sedov-Taylor, or “atomic bomb”)
Ejecta are decelerated by a roughly equal mass of ISM $r \sim t^{2/5}$
Energy is conserved
Evolution of density, pressure is self-similar
Temperature increases inward, pressure decreases to zero

Radiative
Dissipation of remnant energy into ISM
Remnant forms a thin, very dense shell which cools rapidly
Interior may remain hot



Shocks compress and heat gas

Mass, momentum, energy conservation give relations (for γ=5/3)

$\rho = 4\rho_0$

$V = 3/4\ v_{shock}$

$T = 1.1\ m/m_H\ (v/1000\ km/s)^2$ keV

X-rays are the characteristic emission

These relations change if significant energy is diverted to accelerating cosmic rays

The shock is "collisionless" because its size scale is much smaller than the mean-free-path for collisions (heating at the shock occurs by plasma processes)

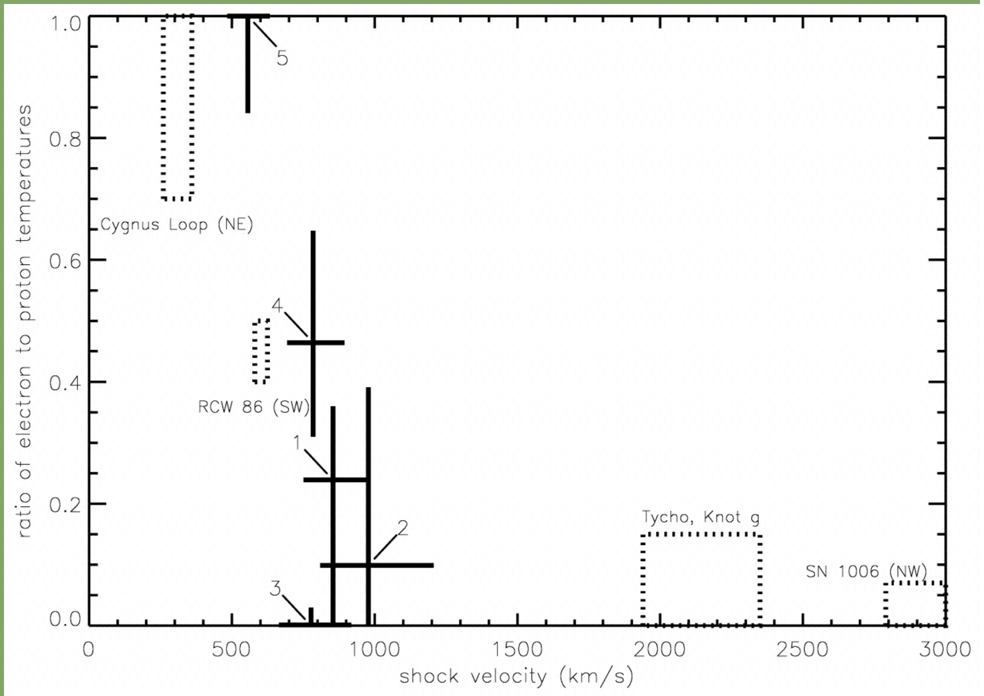
Collisions do mediate ionizations and excitations in the shocked gas

Electron Heating at SNR Shocks
Compare T_e to T_p

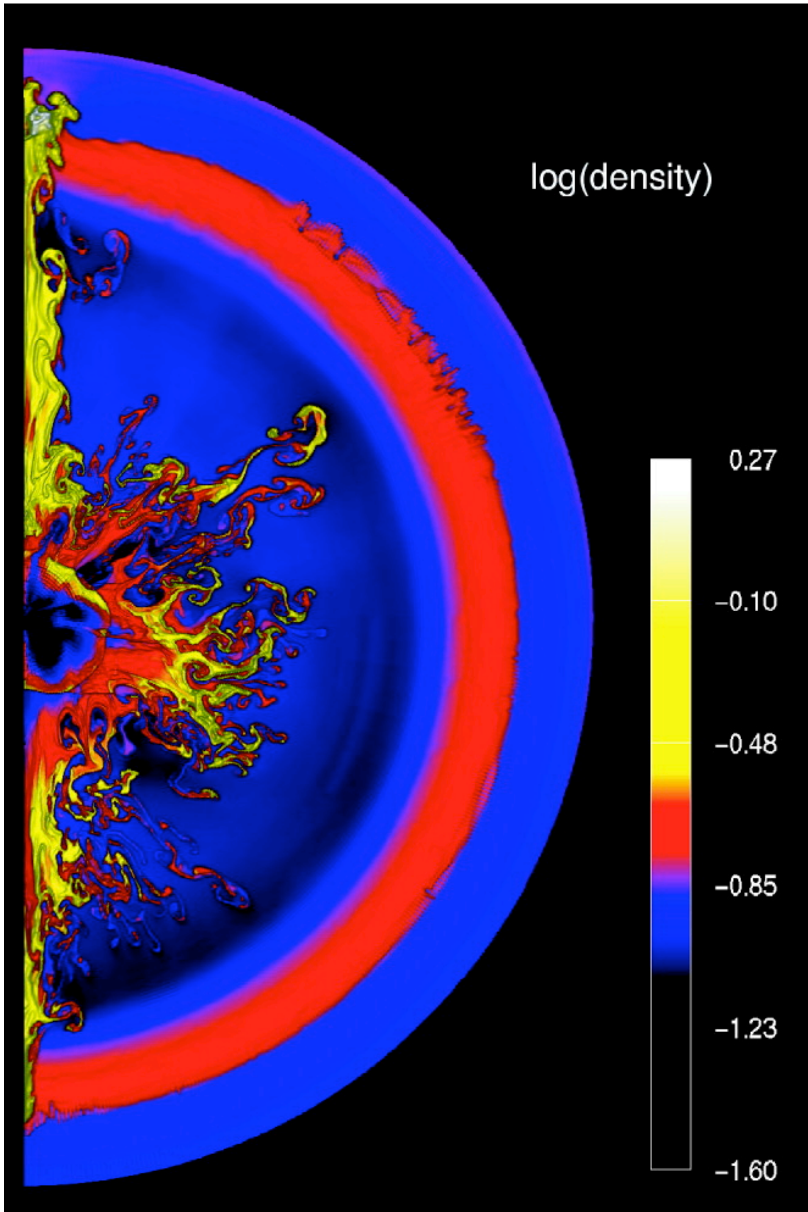
Temperatures behind shock are proportional to mass

Electrons and ions will equilibrate their temperatures by Couloumb collisions, but possibly more quickly by complicated collisionless plasma processes

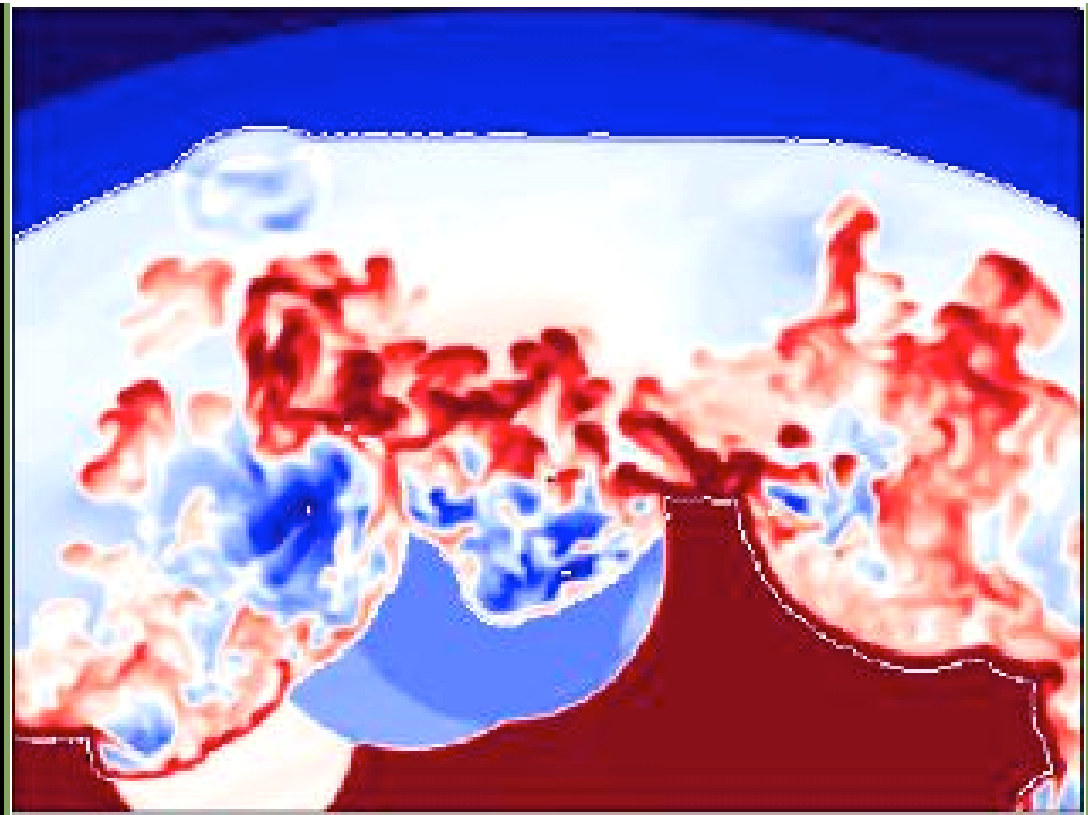
The efficiency of heating depends on the Mach number (shock velocity): faster electron heating in slower shocks



Rakowski et al. 2003



Kifonidis et al. 2000



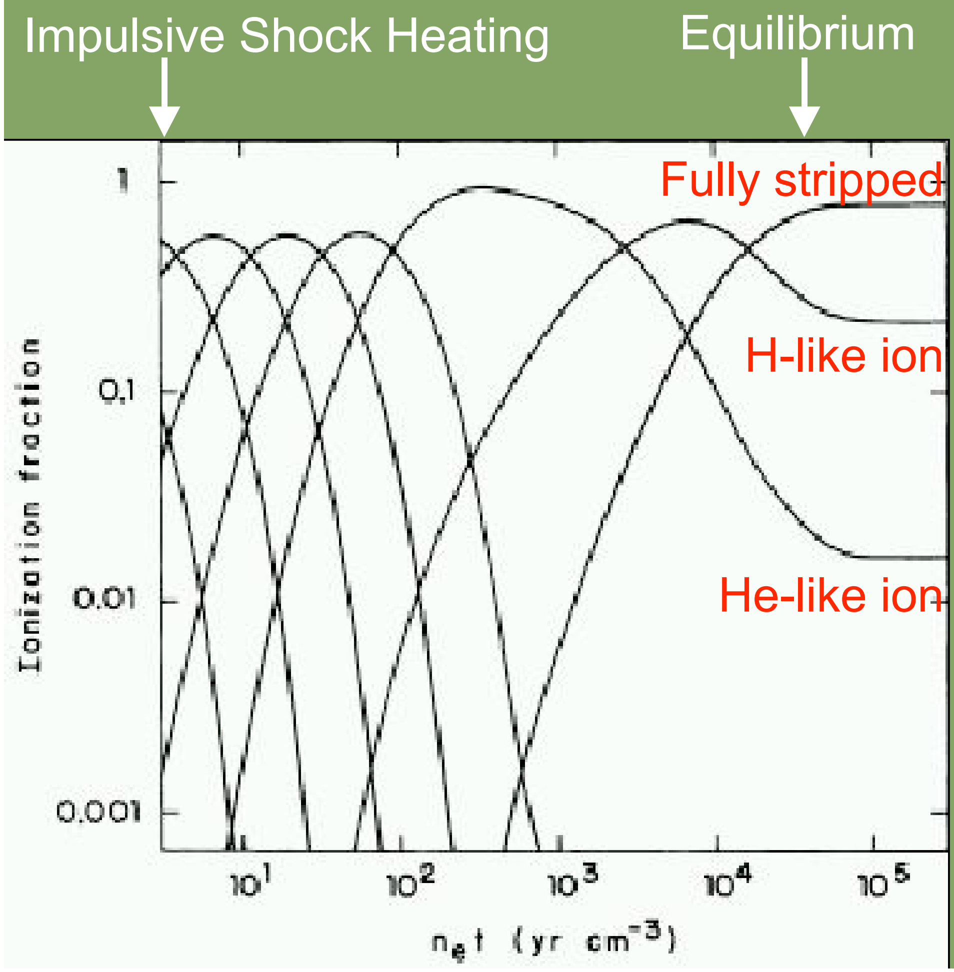
Fe bubbles Blondin et al. 2001

Instabilities

irregular shock boundaries
mixing between ejecta layers
mixing between ejecta and ISM

Time-Dependent Ionization

Oxygen heated to 0.3 keV
(Hughes & Helfand 1985)



Ionization is effected by electron-ion collisions, which are relatively rare in the ~1 cm^{-3} densities of SNRs

Ionization is time-dependent

Ionization timescale = $n_e t$
electron density x time since impulsively heated by shock

Ionization equilibrium attained at $n_e t \sim 10^4$ cm^{-3} yr

Ionizing gas can have many more H- and He- like ions, which then enhances the X-ray line emission

Inferred element abundances will be too high if ionization equilibrium is inappropriately assumed for an ionizing gas

Supernovae and Supernova Remnants

Supernovae

powered mostly by radioactive decay: $^{56}\mathrm{Ni} \rightarrow {}^{56}\mathrm{Co} \rightarrow {}^{56}\mathrm{Fe}$

$T \sim 5000$ K

characteristic emission is optical and infrared

timescale ~ year

Supernova remnants

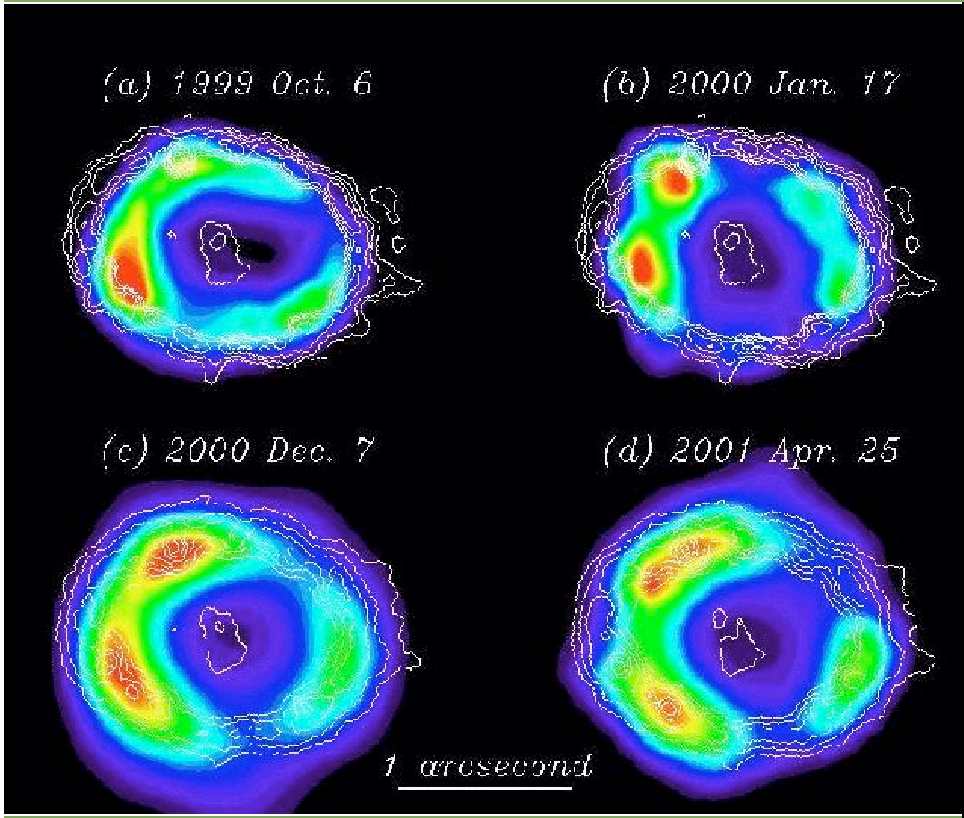
powered by expansion energy of supernova ejecta, dissipated as the debris collides with interstellar material generating shocks

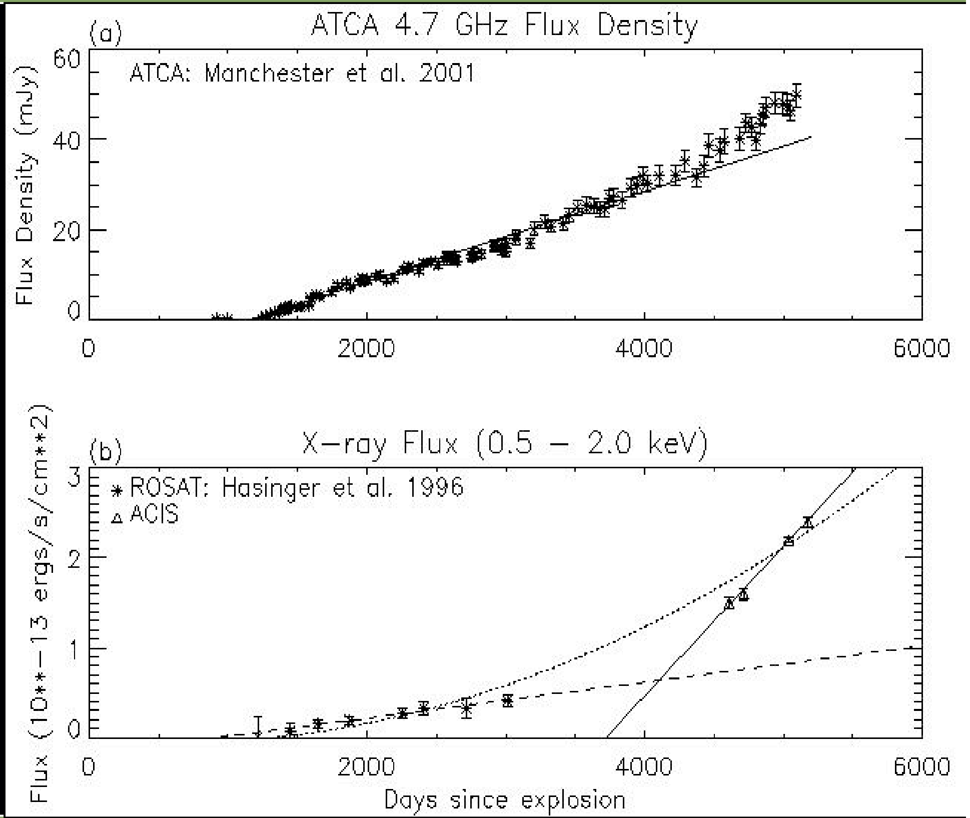
$T \sim 10^{6-7}$ K

characteristic thermal emission is X-rays

timescale ~100-1000 years

SNR 1987A in Large Magellanic Cloud





Park et al. 2002 , Burrows et al. 2001

X-ray emission is approaching inner circumstellar ring
X-rays correlate well with radio

X-ray Emission from Supernova Remnants

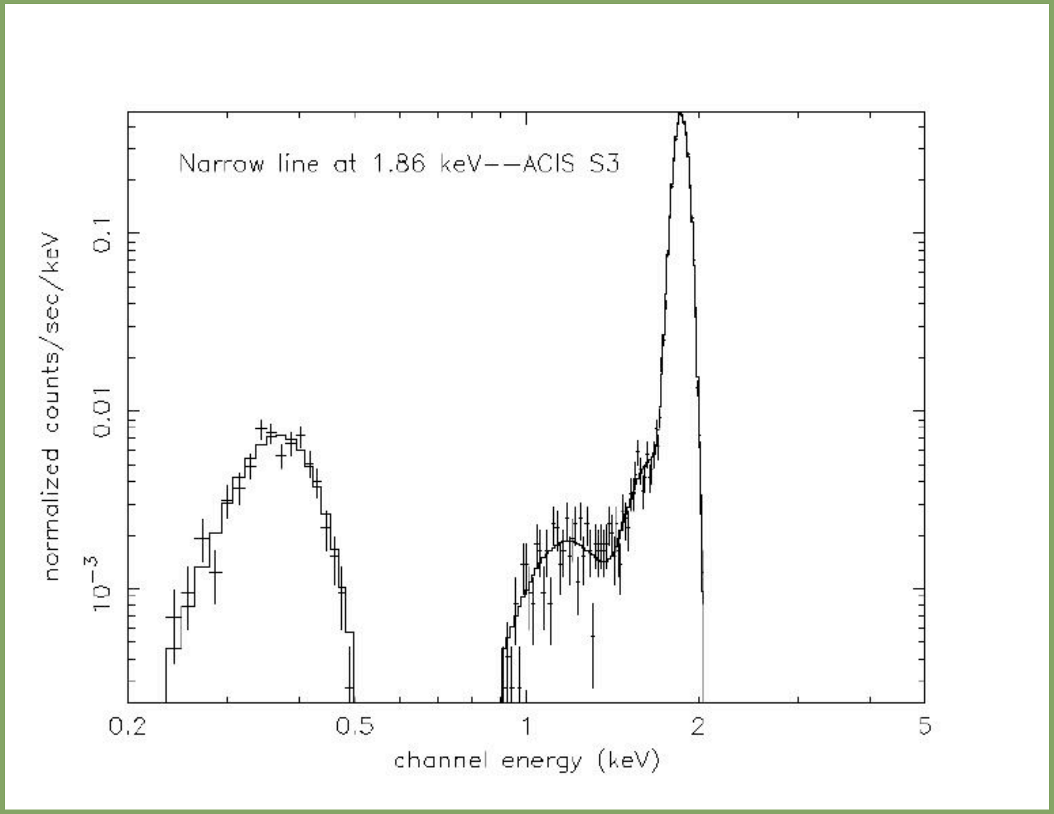
Thermal Emission

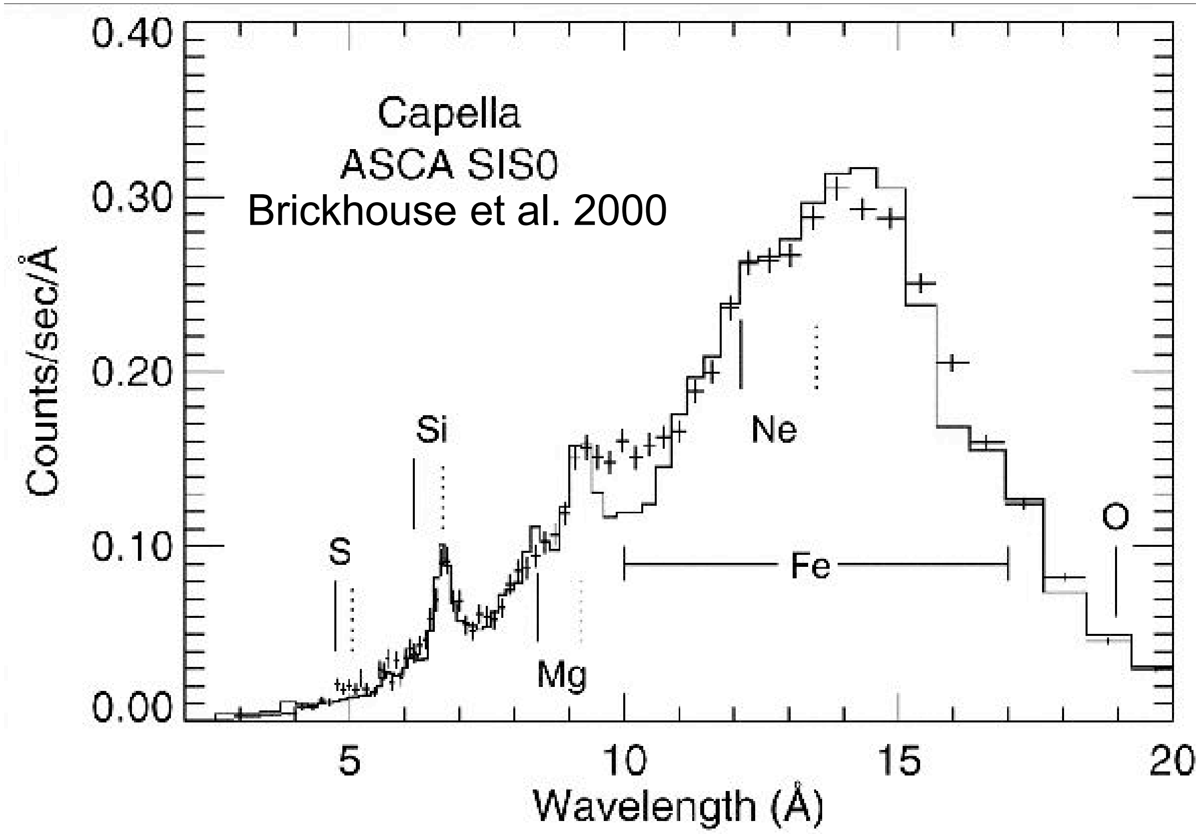
- characterized by electron temperature, ionization timescale, element abundances
- primarily bremsstrahlung continuum
- collisionally excited emission lines ⇣

Nonthermal Emission

- blackbody or power law from pulsar/neutron star if present (across electromagnetic spectrum)
- synchrotron emission from electrons accelerated at the shock (usually radio, sometimes up to X-rays)

The model is multiplied by the detector effective area and folded through a matrix that distributes photons of a given energy over the appropriate range of pulse height values.



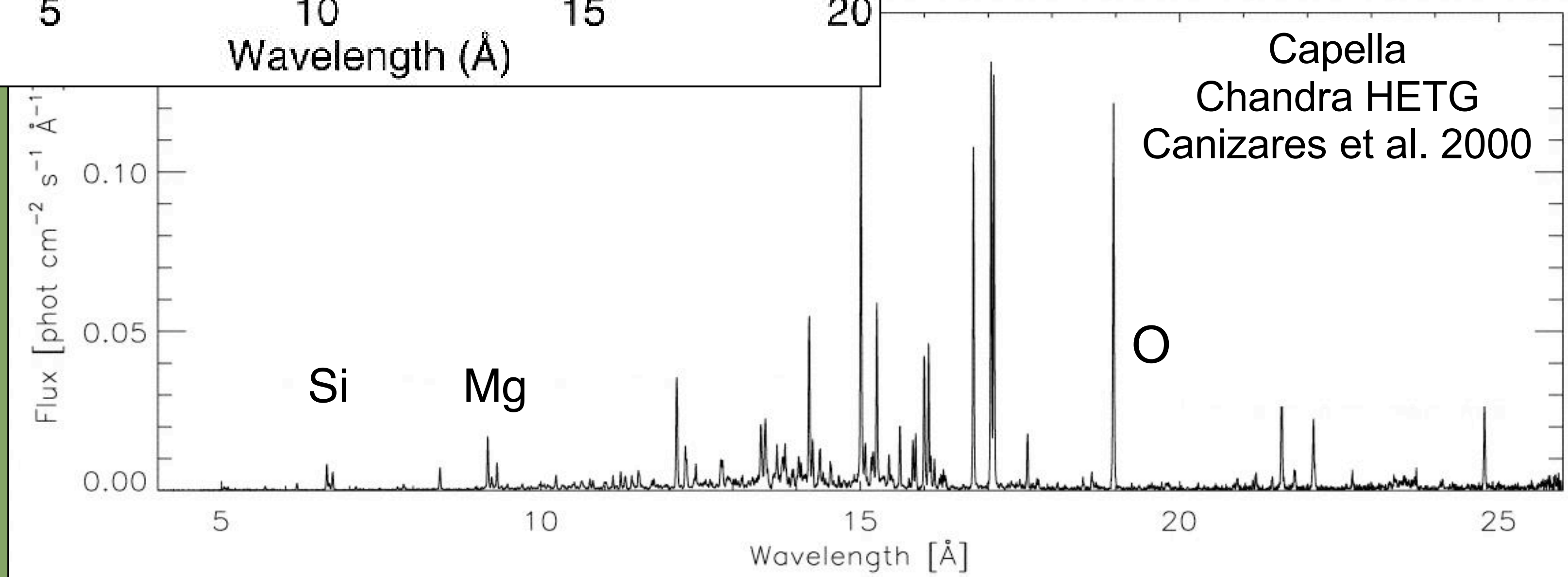


CCD

Spectral Resolution

CCD devices have limited spectral resolution:

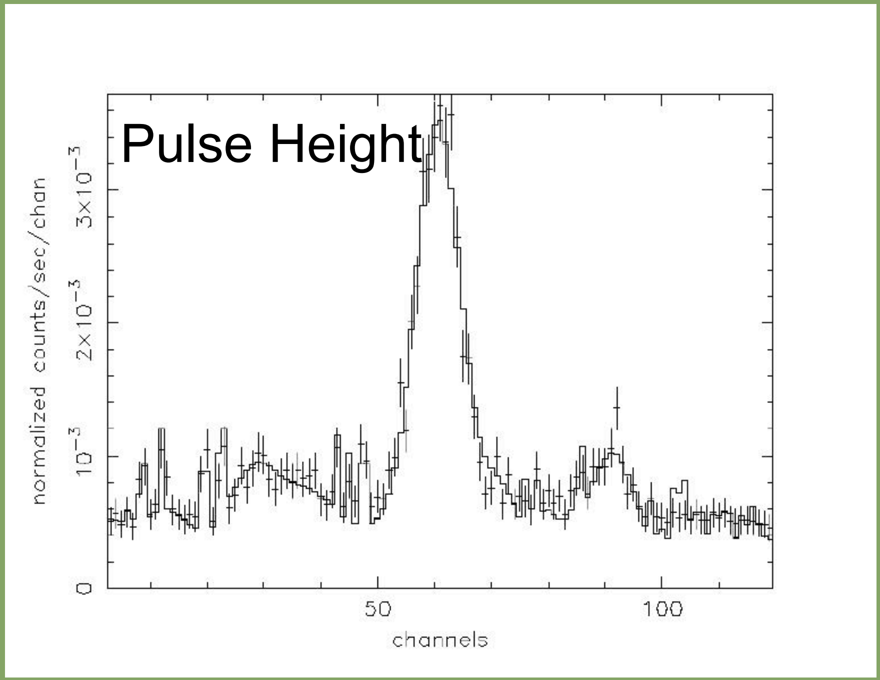
“line” features in CCD spectra are generally blends of multiple emission lines

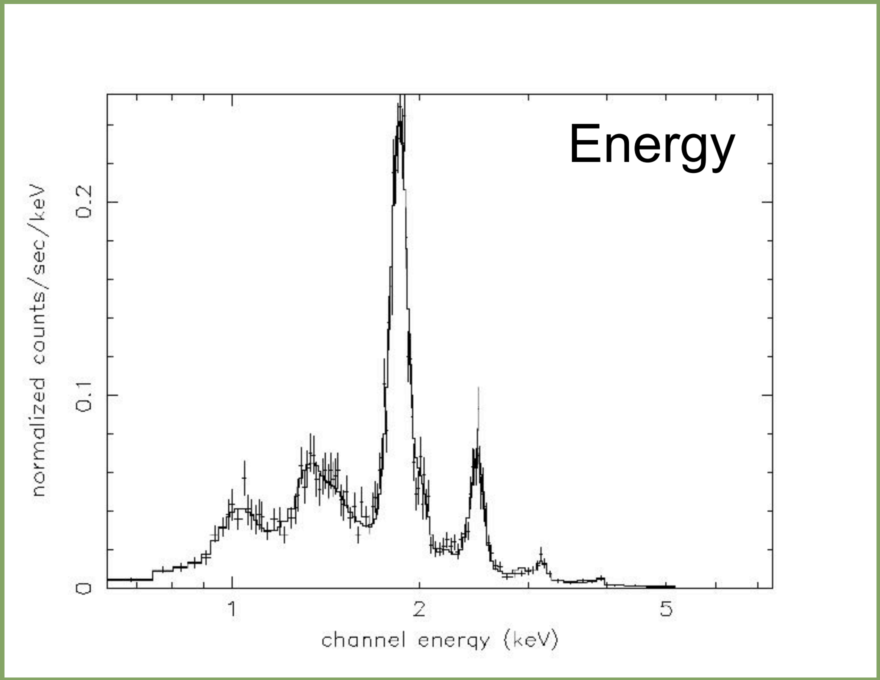


Transmission Grating

Broadband X-ray Spectral Fitting

Data are accumulated by the detector as counts per pulse height bin. The detector "gain" gives the average relation between pulse height bin and photon energy.





Why Study Supernova Remnants?

Supernova explosion:

How is mass and energy distributed in the ejecta?
What was the mechanism of the supernova explosion?
What elements were formed in the explosion, and how?
What are the characteristics of the compact stellar remnant?

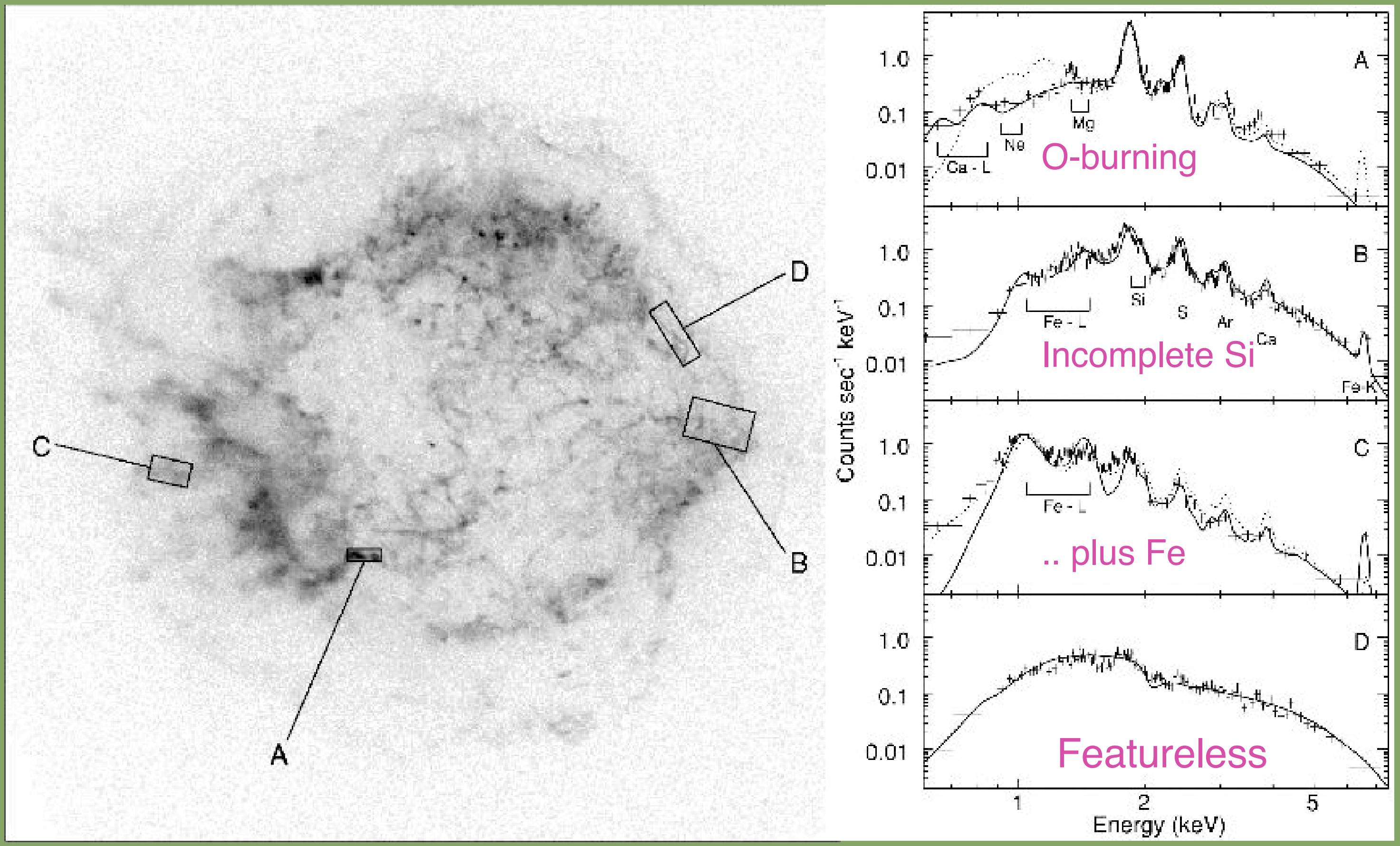
Shock physics:

How is energy distributed between electrons, ions, and cosmic rays in the shock?
How do electrons and ions share energy behind the shock?

Interstellar medium:

What is the structure of the interstellar medium, and how does the shock interact with that structure?

Cassiopeia A: Explosive Nucleosynthesis



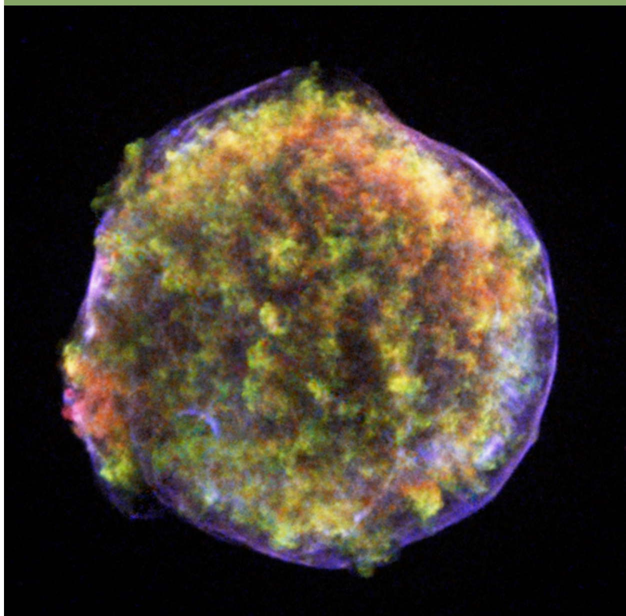
(Hughes et al. 2000 ApJ, 518, L109)

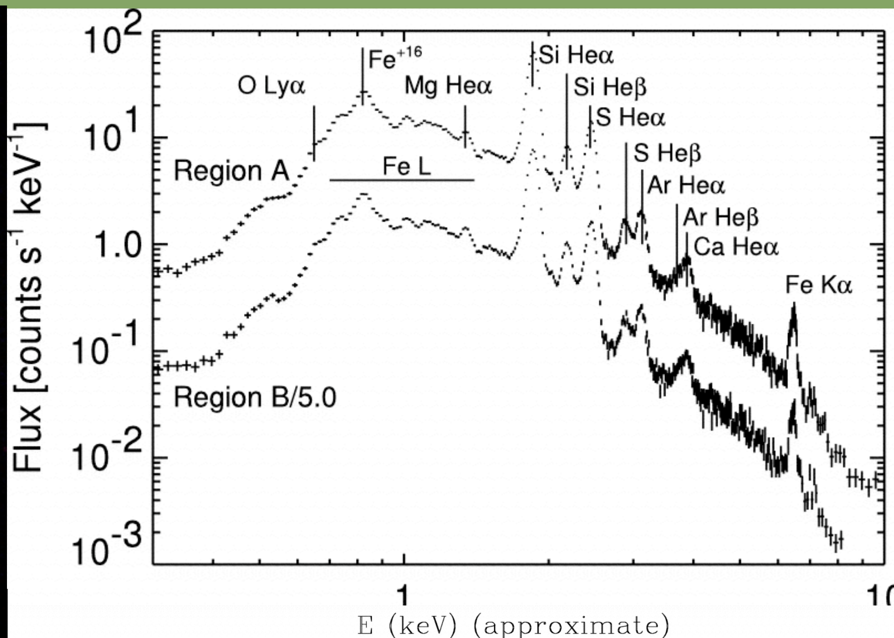
Explosive Nucleosynthesis

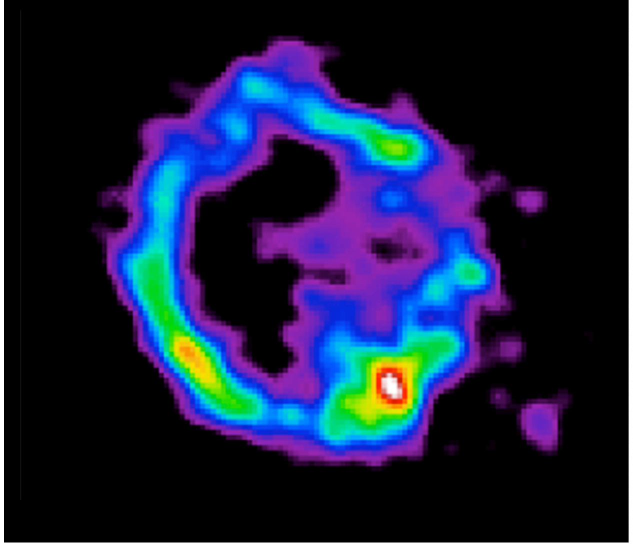
Nuclear processing as the supernova shock wave propagates through the star (e.g., see Arnett 1996)

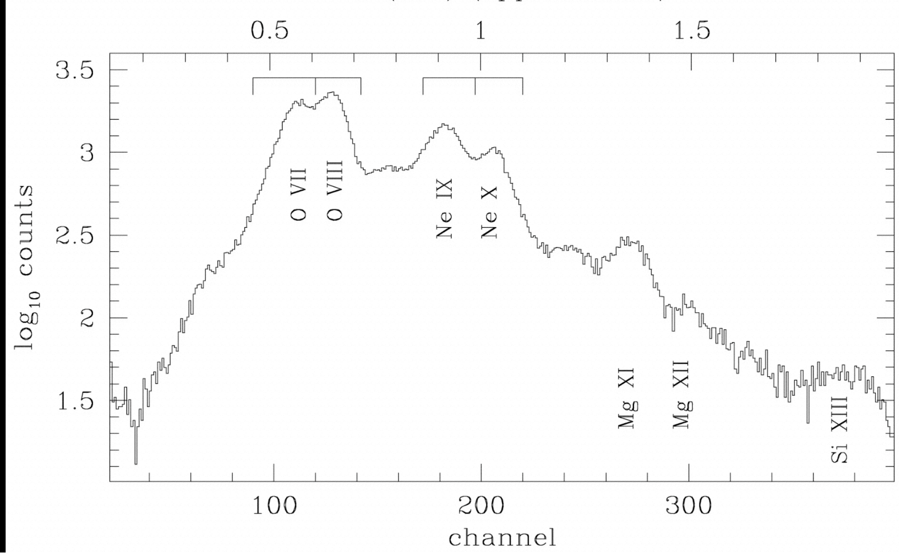
C burning produces O, Ne, Mg, etc	$T \sim 2 \times 10^9$ K
Ne burning produces O, Mg, etc	$T \sim 2.3 \times 10^9$ K
O burning produces Si, S, Ar, Ca, etc	$T \sim 3.5 \times 10^9$ K
Si burning produces Fe, Si, S, Ca, etc	$T \sim 5 \times 10^9$ K

Nucleosynthesis Products in SNRs









Tycho's SNR

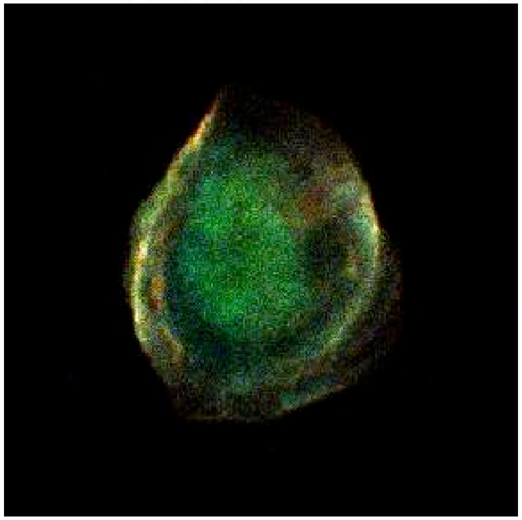
Type Ia
White dwarf + companion

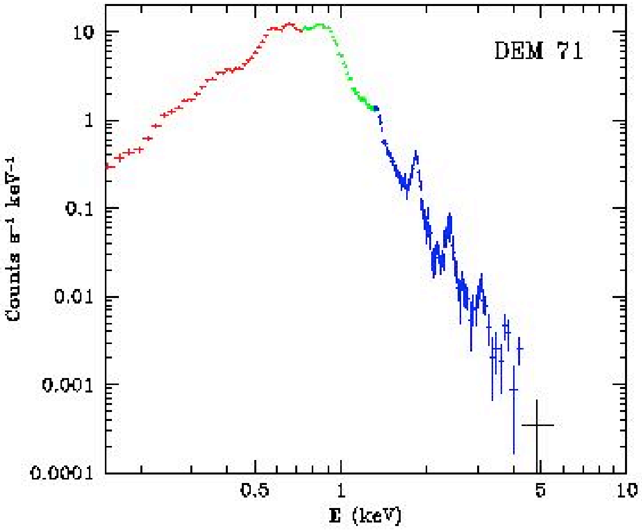
Si, S, Ar, Ca
Expect lots of Fe: most not yet shocked

E0102-72

Core-collapse
~25 M_{sun}
mostly O, Ne, Mg

Identifying Ejecta in Middle-Aged SNRs





DEM L71 in LMC

Outer shock identified; follows optical Hα emission (Ghavamian et al. 2003, Rakowski et al. 2003)

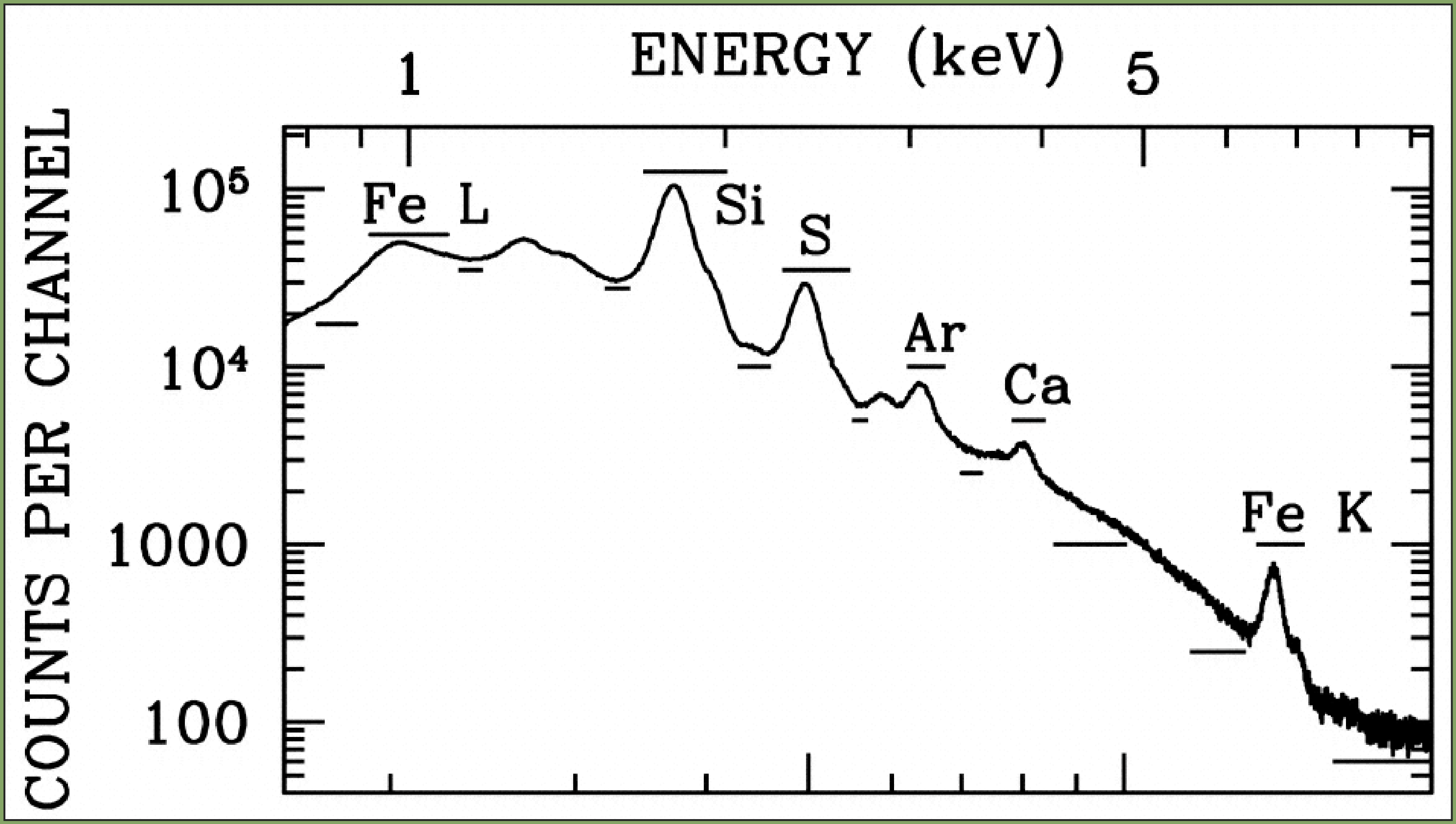
Central X-ray emission is dominant in Fe L emission (n=2 transitions, ~1 keV)

Enhanced Fe abundances in center

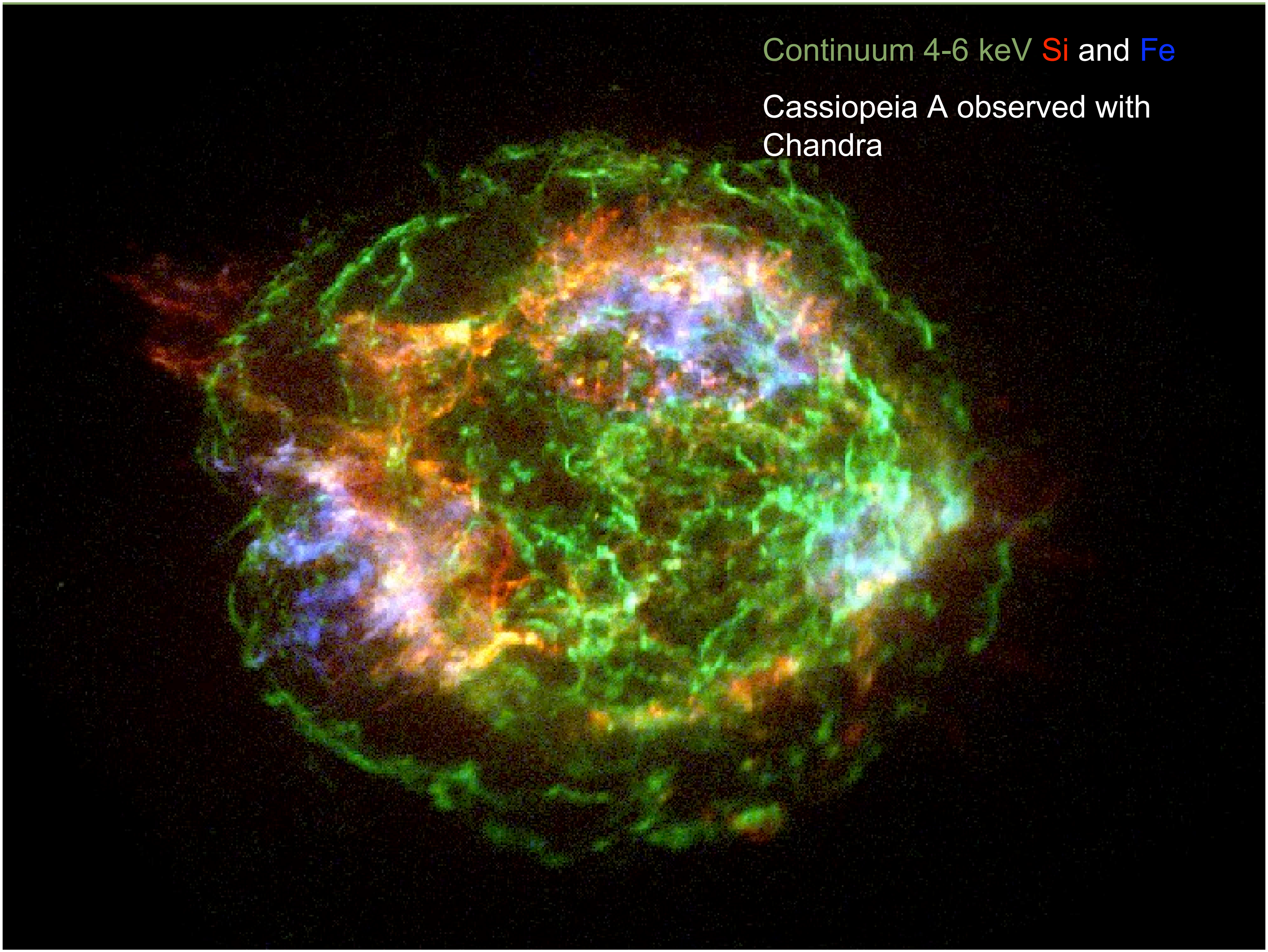
Position of the CD relative to shock gives shocked ejecta mass ~1.5 solar mass probably Type Ia

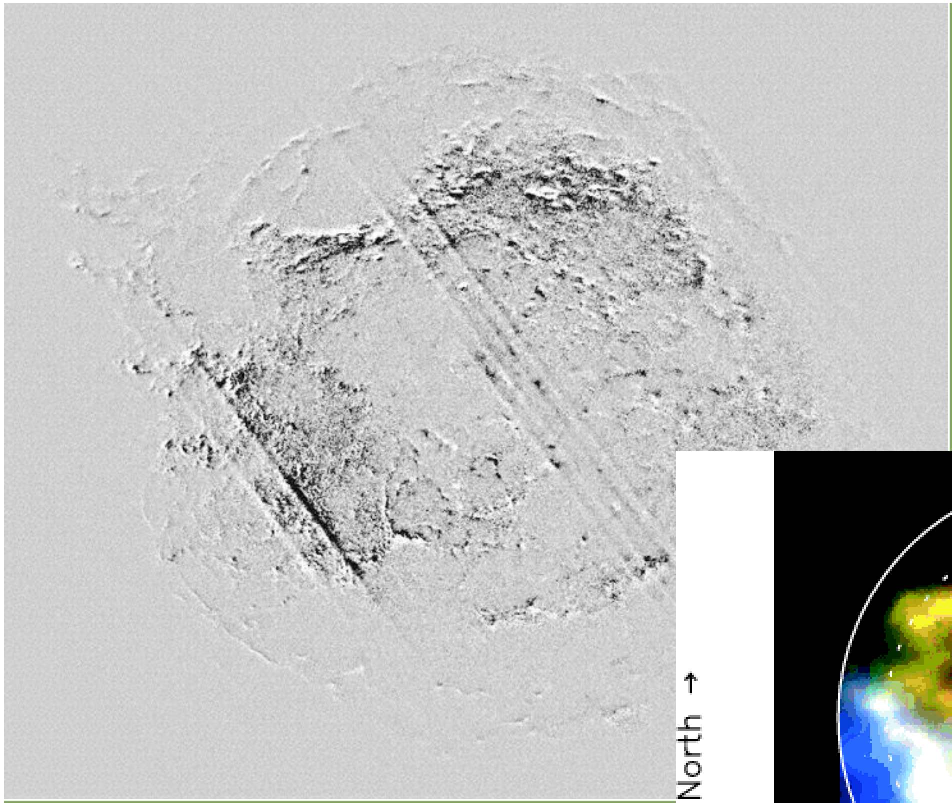
Hughes et al. (2003 ApJ, 582, L95)

Energy Selected X-ray Imaging

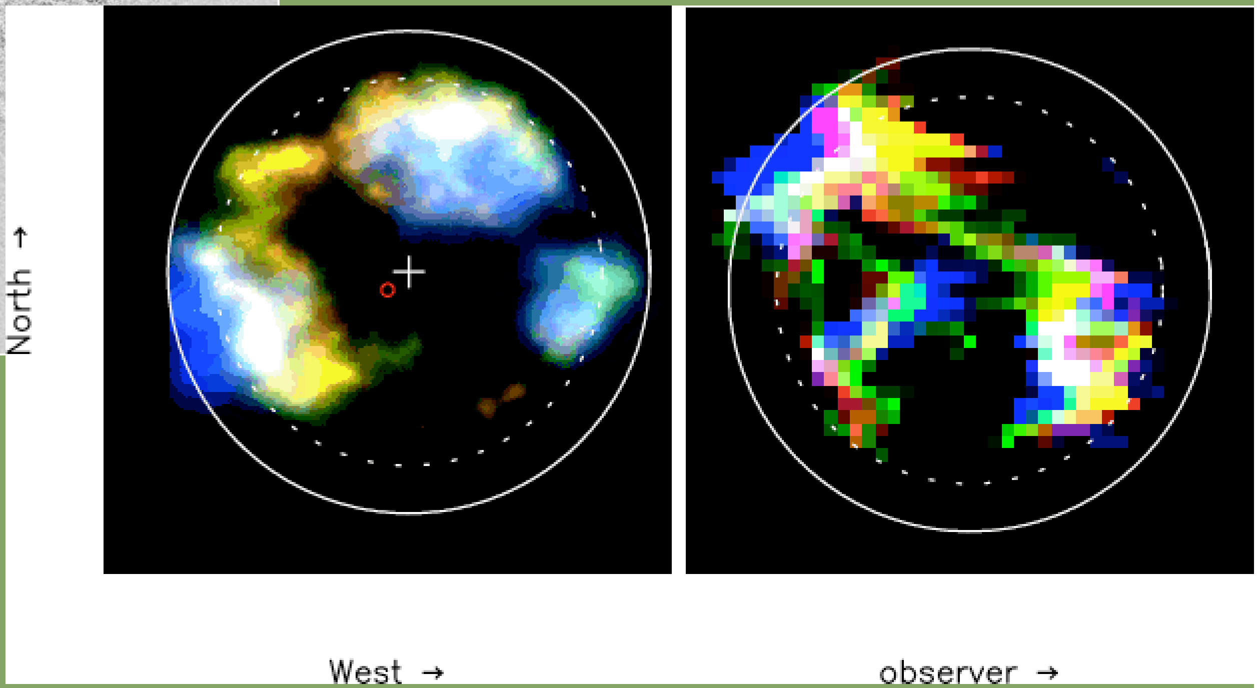


Cassiopeia A Chandra ACIS spectrum


Continuum 4-6 keV Si and Fe
Cassiopeia A observed with Chandra



Doppler shifts
Line of sight velocity



Si K (red) S K (green) Fe K (blue)

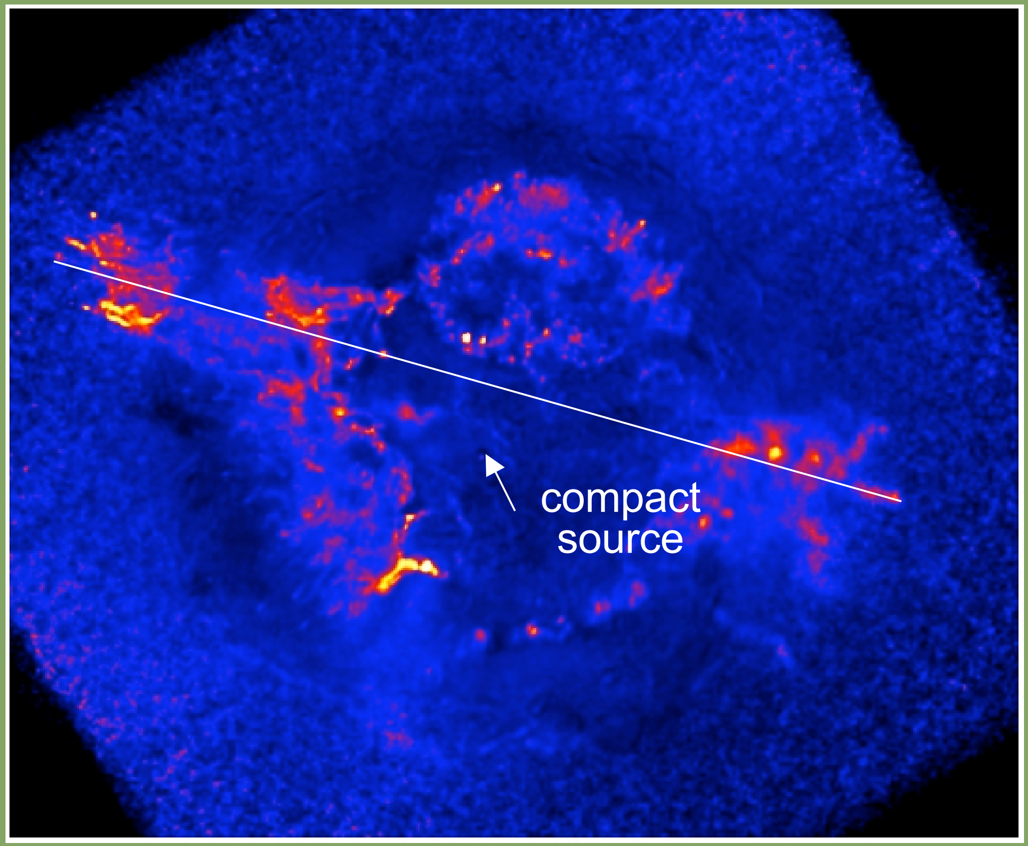
Difference Image for two epochs

Transverse velocity

DeLaney & Rudnick 2003
DeLaney et al. 2003

Willingale et al. 2001

Bipolar “jets” in Cassiopeia A

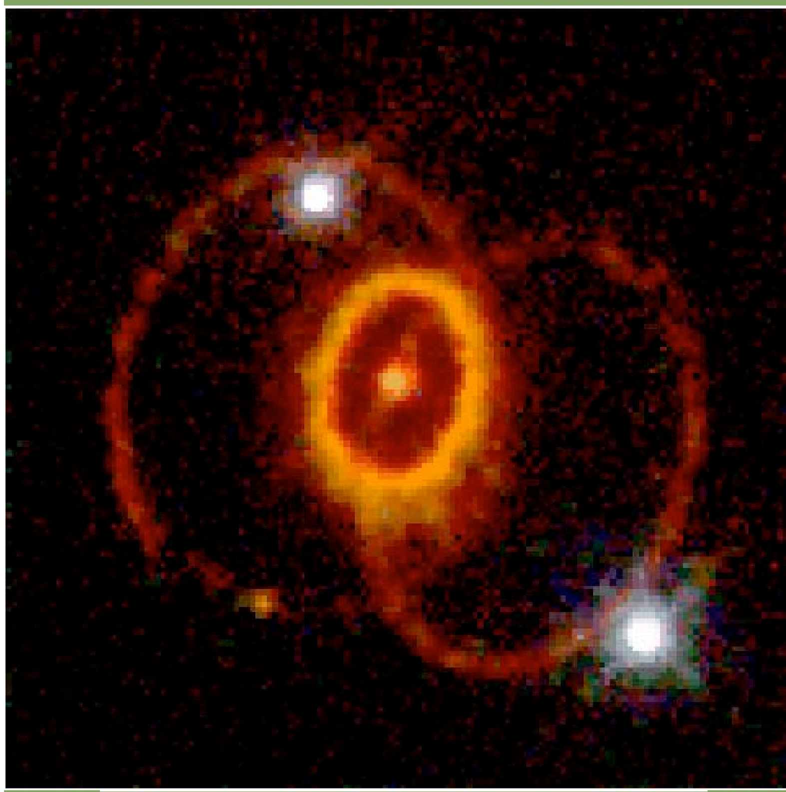


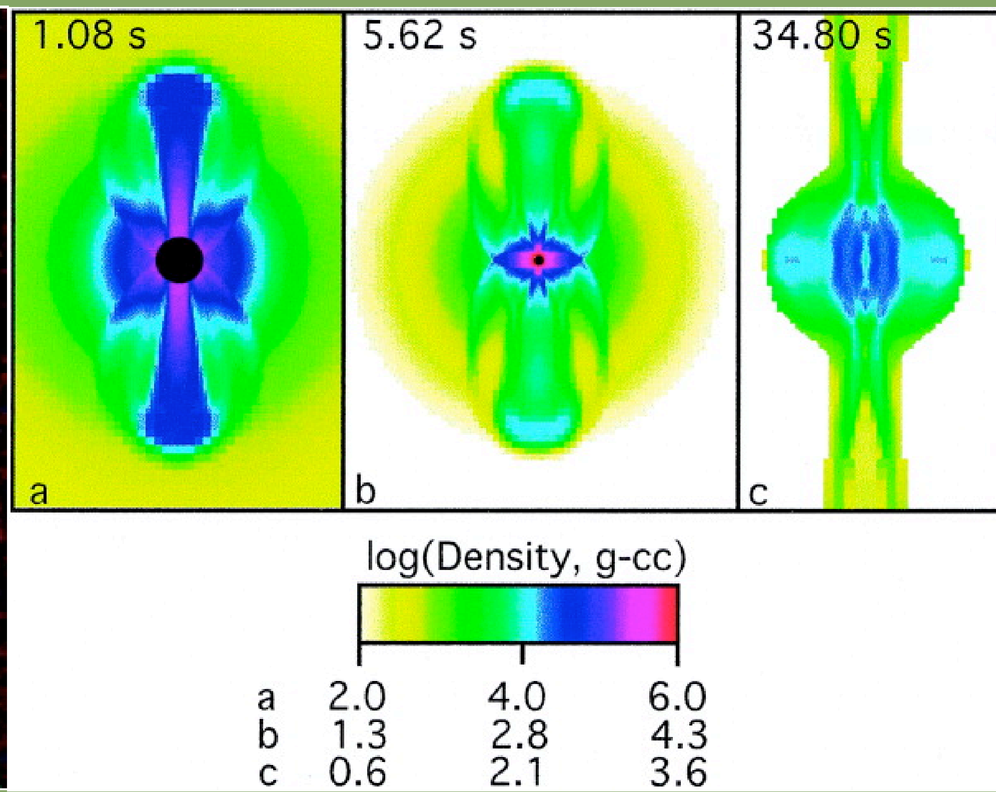
Si Heα/Mg
Heα ratio image

What causes the bipolar morphology in Cas A?

Circumstellar cavity
formed by progenitor

Jets of ejecta





(Blondin et al. 1996)

(Khokhlov et al. 1999)

Interpreting Thermal SNR Spectra

Time evolution of density, pressure, temperature in the remnant

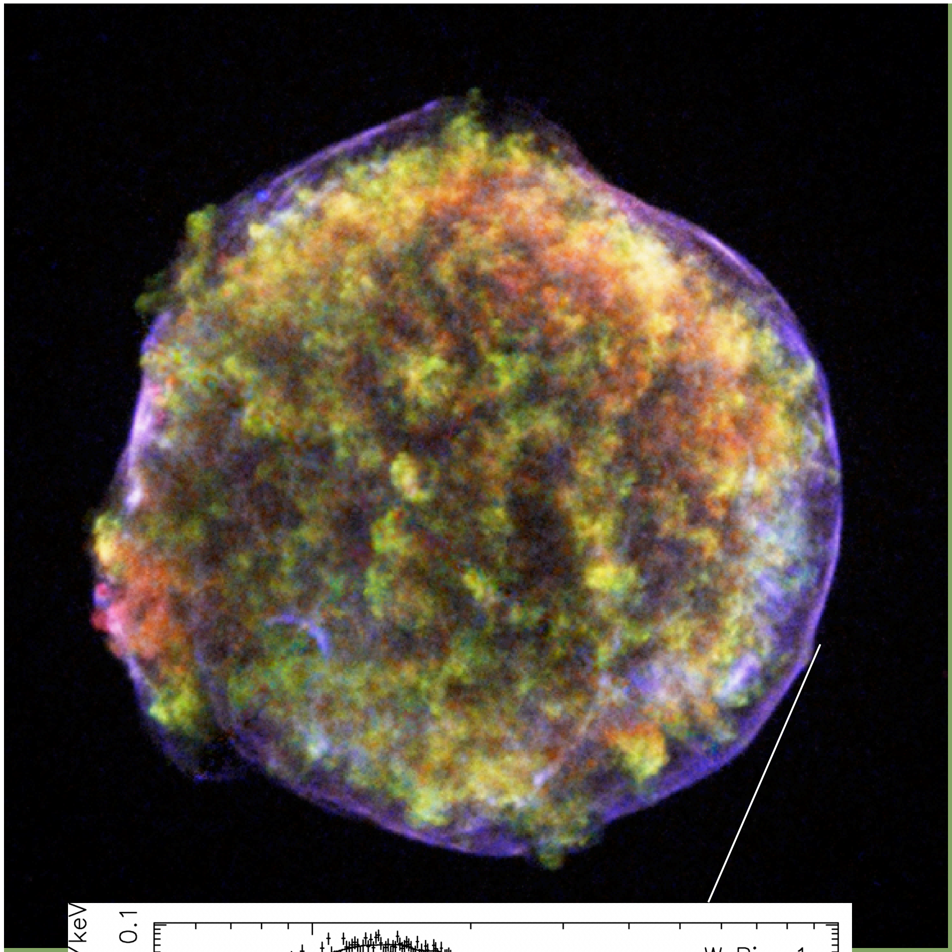
- expansion of the gas (P=nkT)
- cooling of the gas by line emission
- heating of the gas by collisions, radiation
- loss of energy to particle acceleration

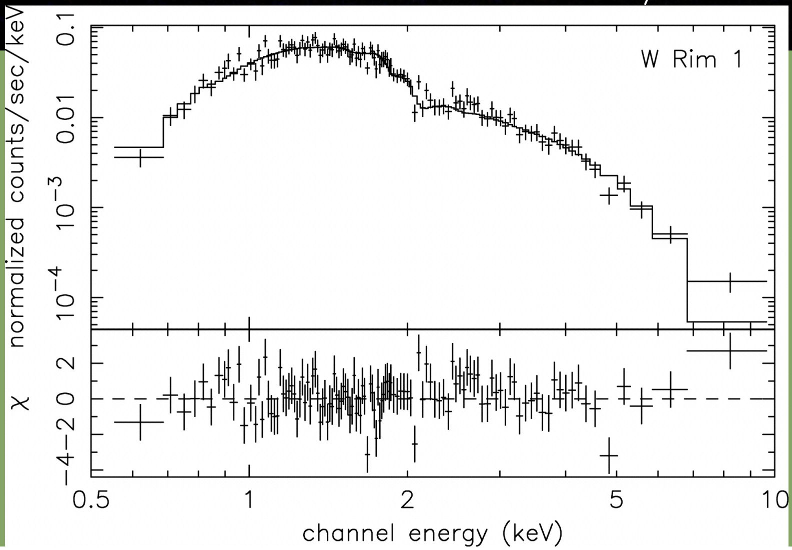
Atomic processes in the gas

- collisional ionization
- excitation of ions and emission of radiation

Things to keep in mind:

- emission is weighted by n^2V: denser gas is brighter
- line emission is proportional to ion abundance:
  - no lines in fully ionized gas, or gas that is too cold to be ionized
- nonthermal continua may be present (e.g., synchrotron)



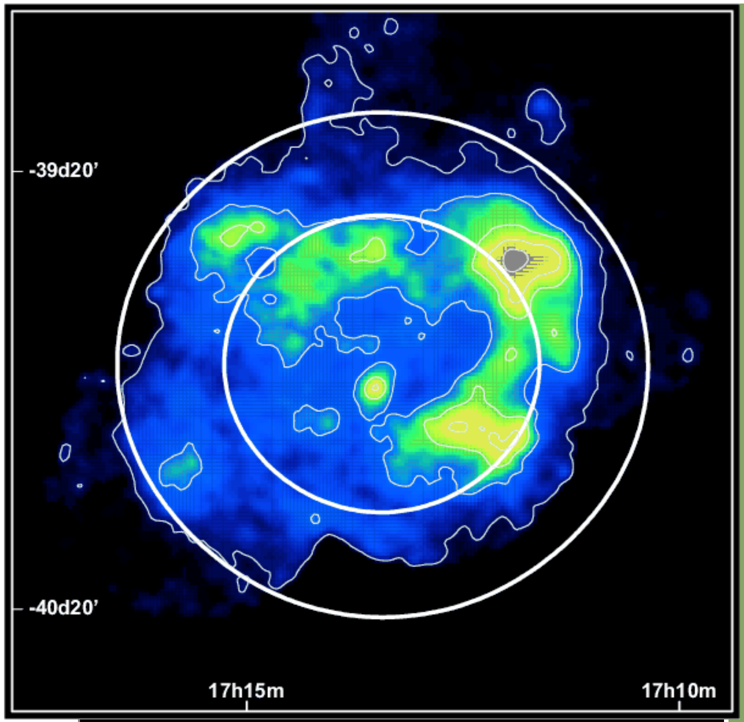


Tycho's SNR (SN 1572)

Mostly thermal emission from ejecta (Si and Fe ejecta)
Rim emission is thermal + nonthermal
(Hwang et al. 2002)

Proximity of ejecta to FS is inconsistent with age, observations for models for adiabatic remnants
Implies efficient acceleration of cosmic rays
(Warren et al. 2005)

Knowing physical scale, width of synchrotron filaments can be used to infer B field
B~100μG

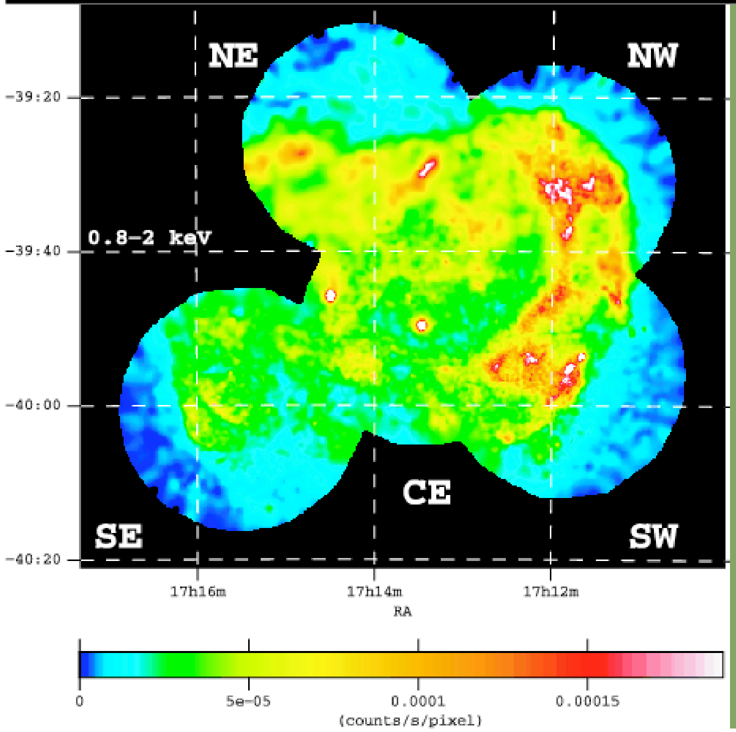


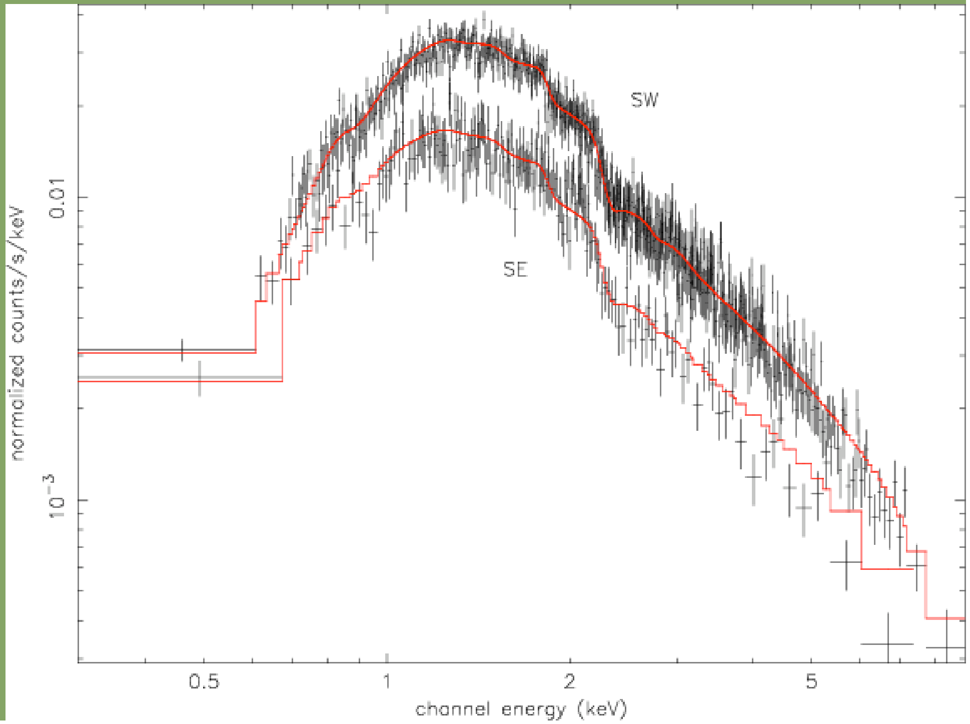
RXJ1713-3946

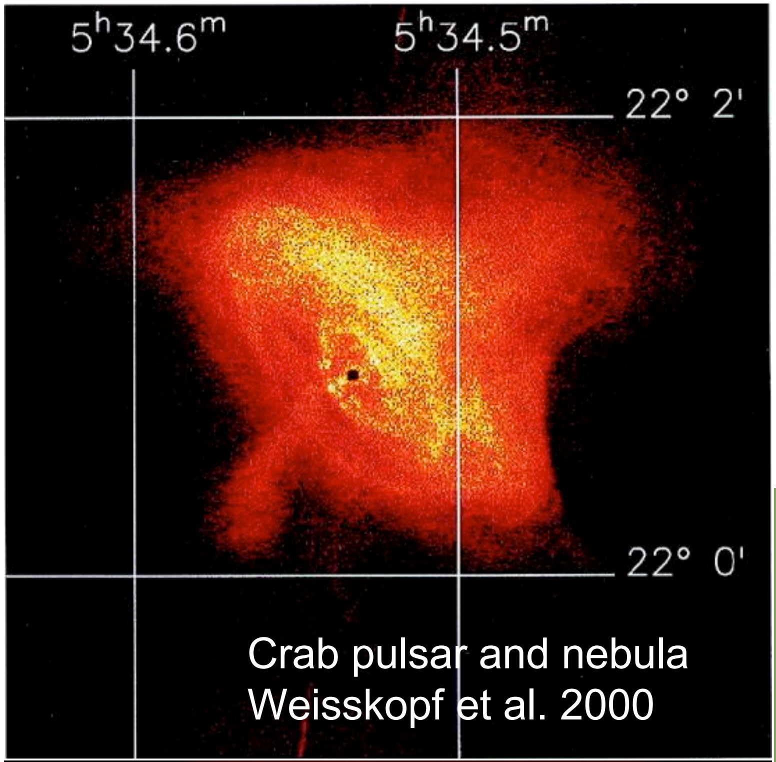
Like SN1006 is dominated in X-rays by synchrotron emission

PL spectrum with $\Gamma \sim 2.2\text{–}2.3$

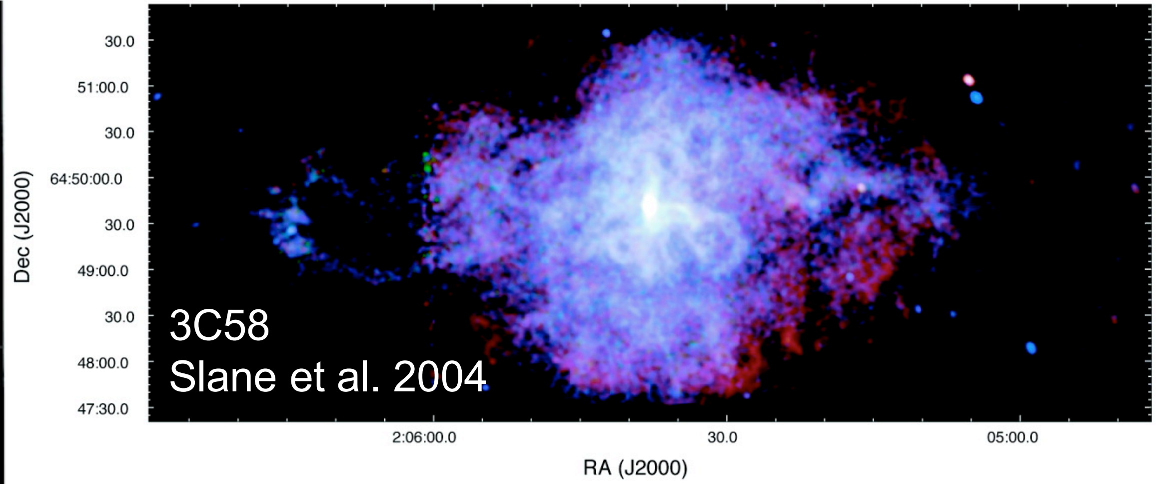
(Uchiyama et al. 2002, Cassam-Chenai et al. 2004)







Crab pulsar and nebula
Weisskopf et al. 2000

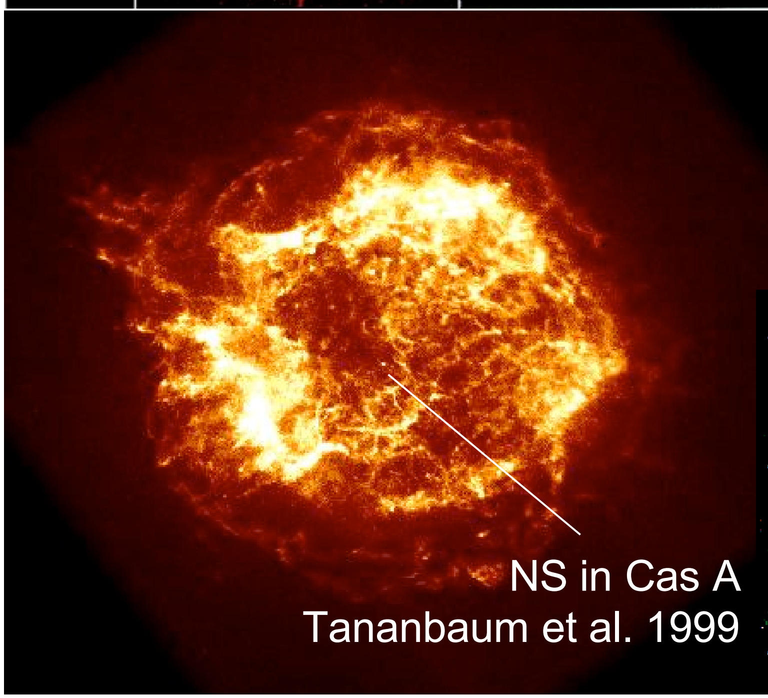


3C58
Slane et al. 2004

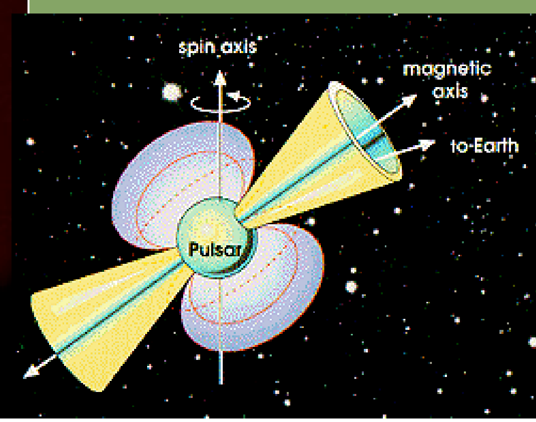
Neutron Stars in SNRs

Pulsars are highly magnetized NS: beacons of light emitted along axis are detected as pulsations

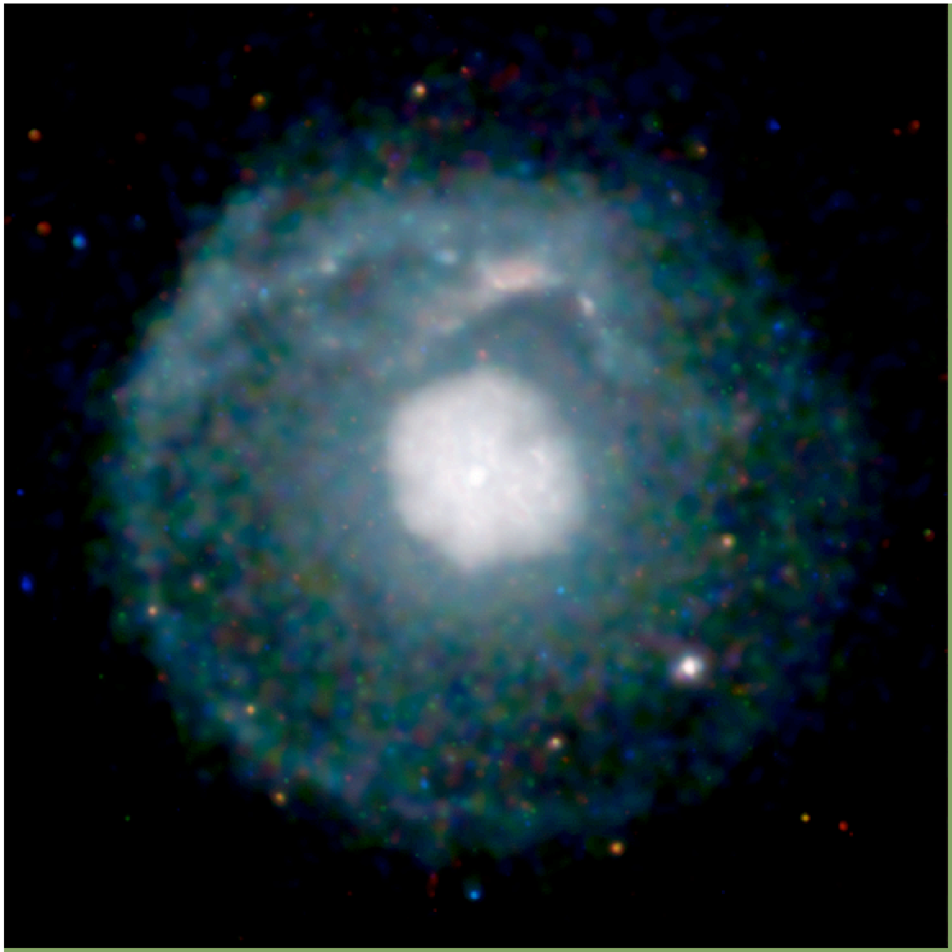
Infer energy loss rate, B field from pulsation characteristics

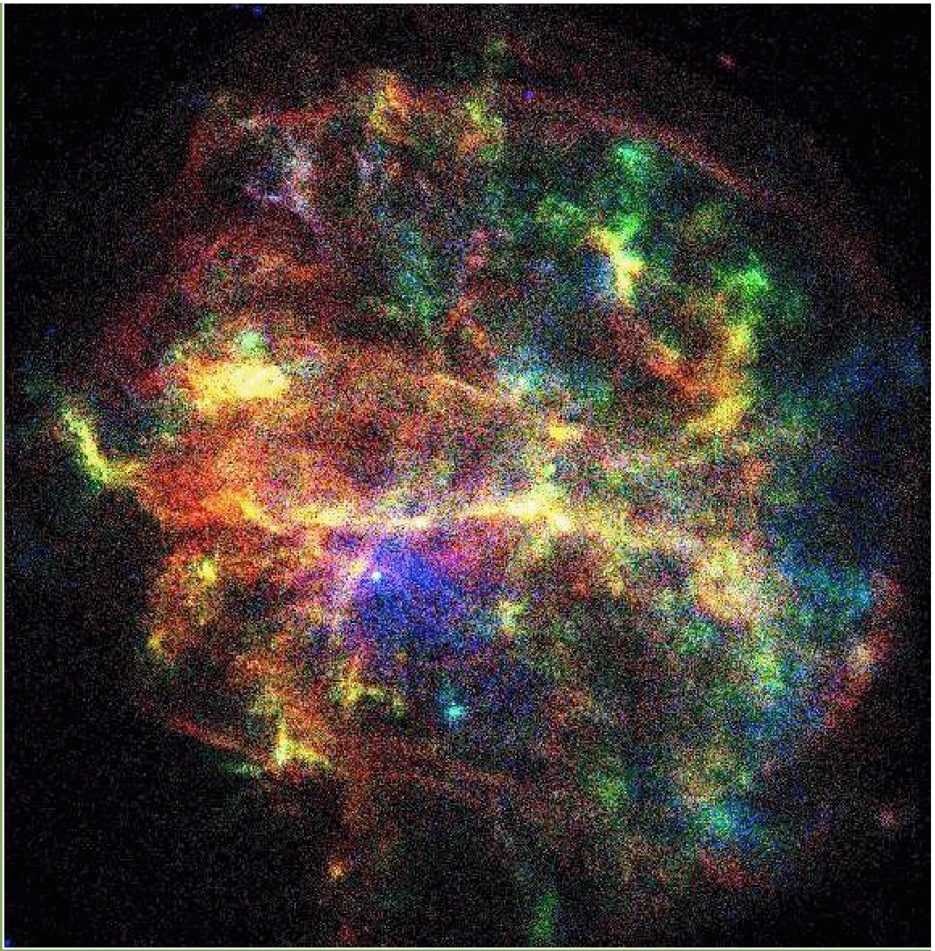


NS in Cas A
Tananbaum et al. 1999



Relativistic wind is seen as a nebula around pulsar
Thermal (blackbody) emission is also emitted from the surface of the NS





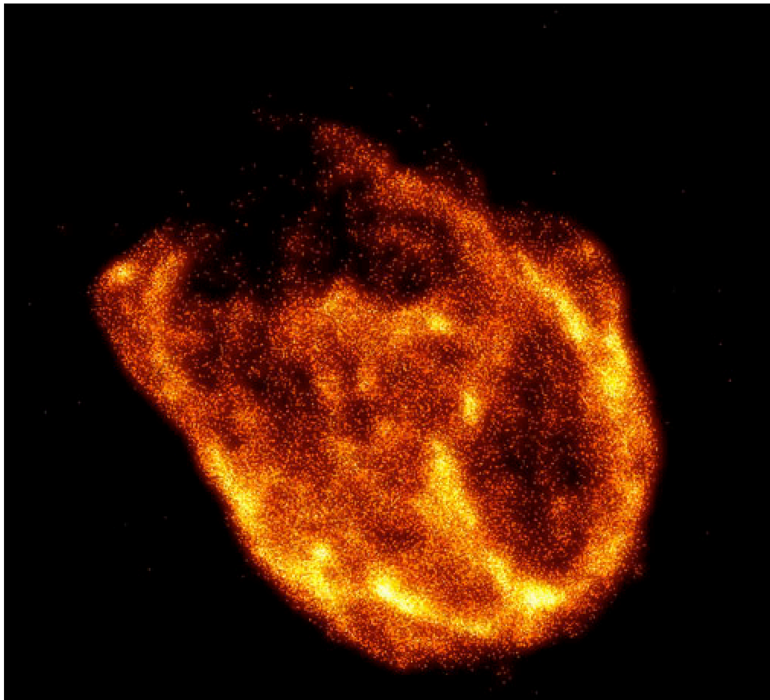
G21.5-0.9

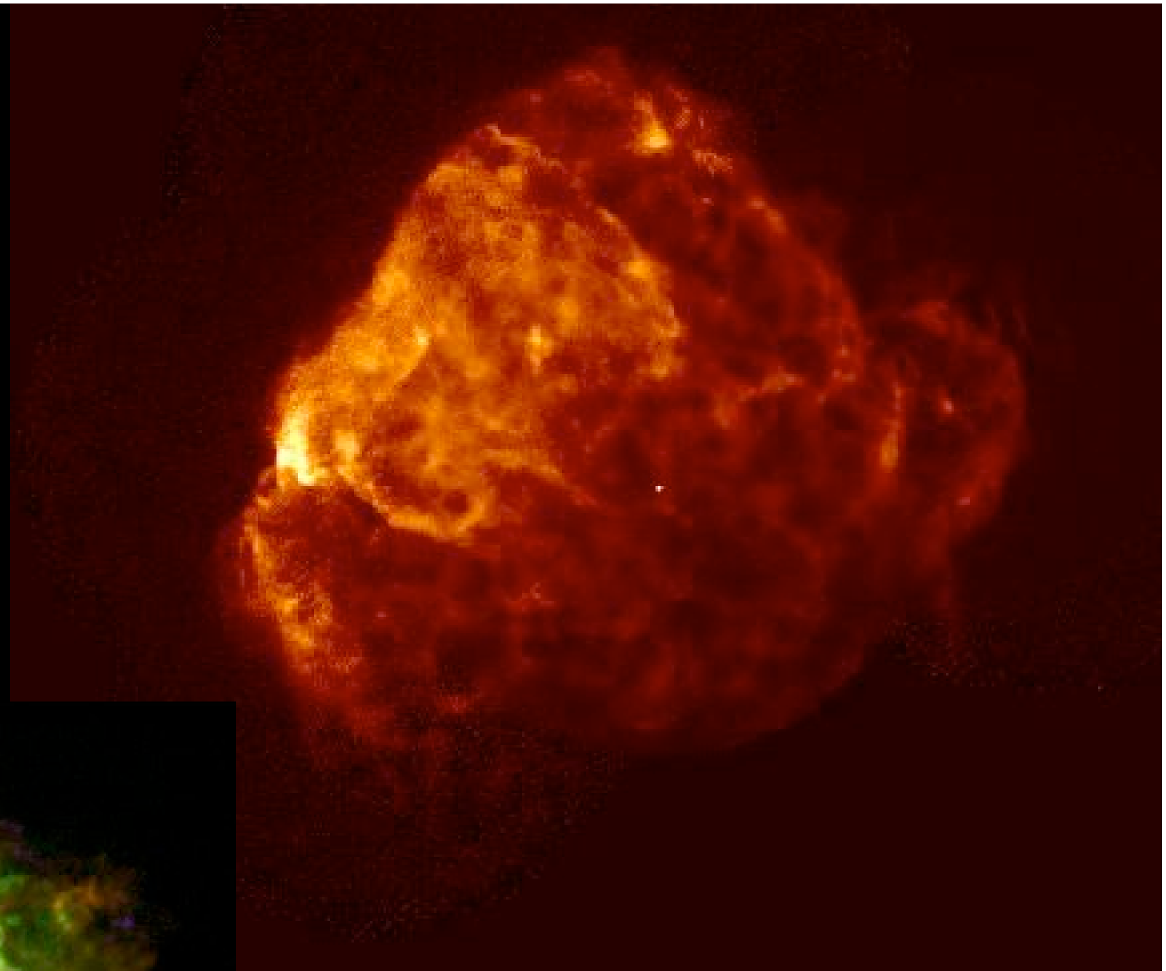
Matheson & Safi-Harb 2004

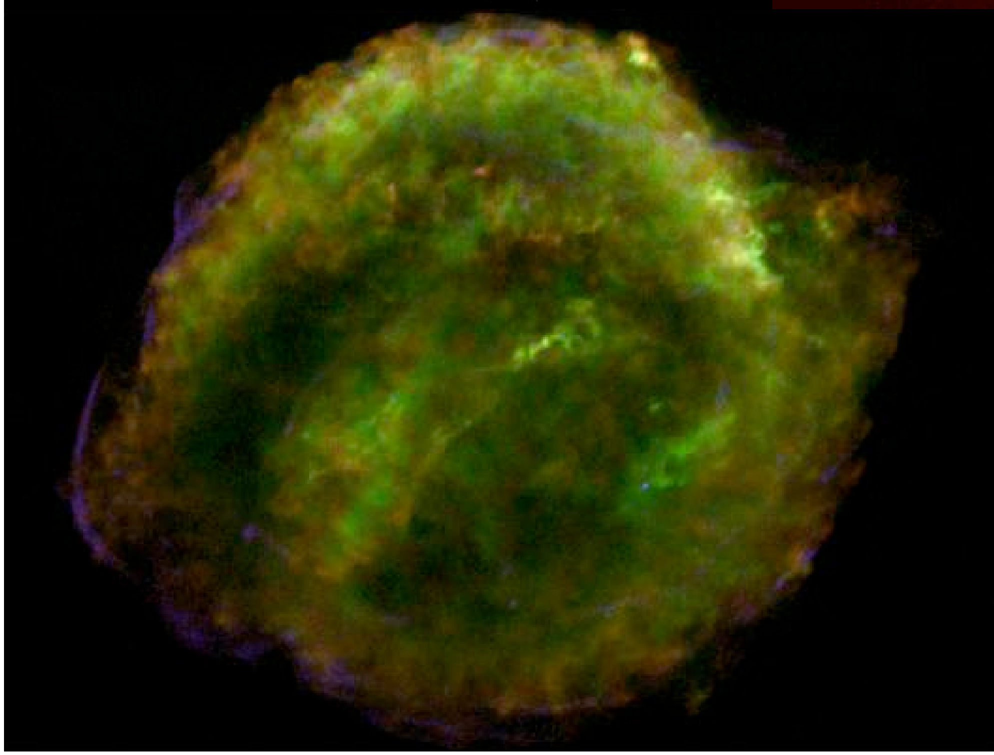
G292.0+1.8

Park et al. 2002, Hughes et al. 2001

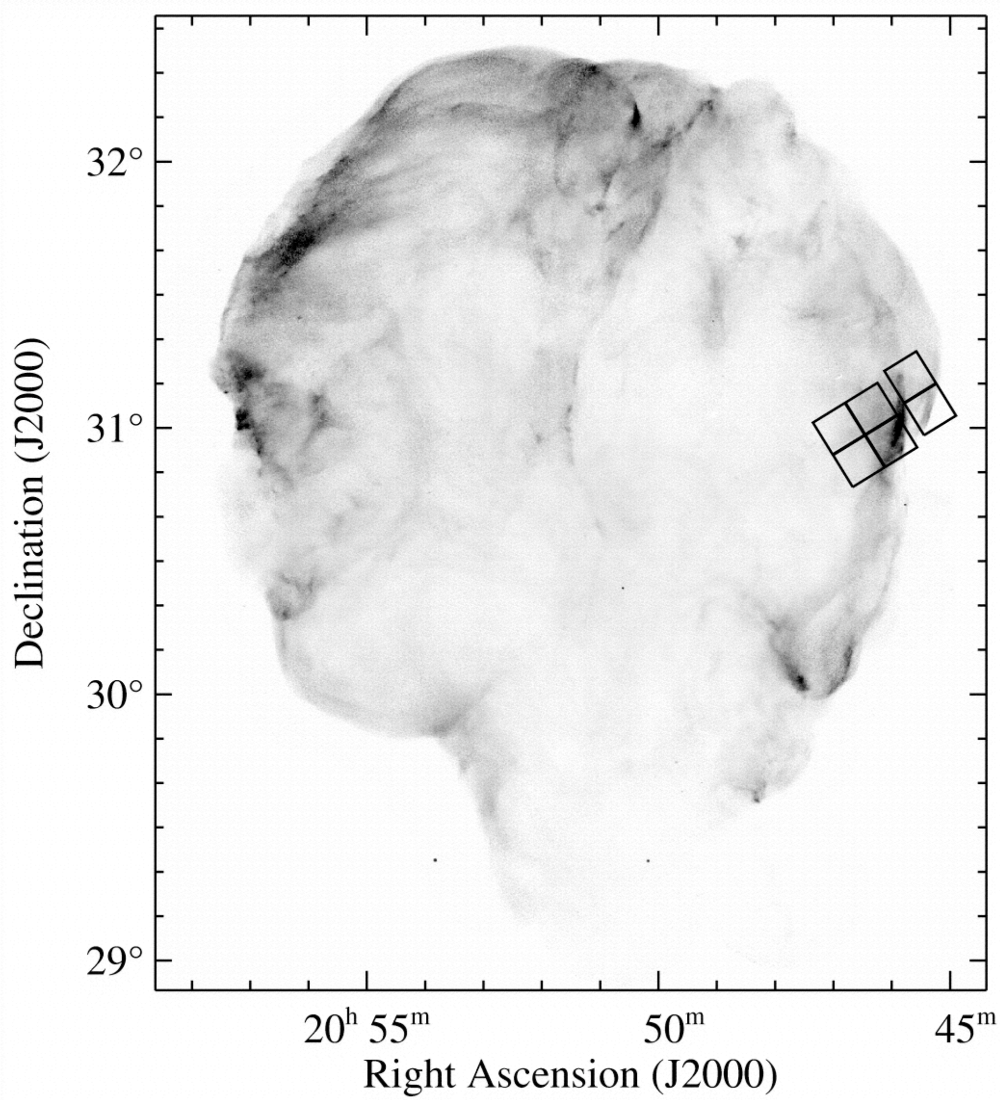
Composite Remnants: Shell + PWN







Examples of
Interstellar/Circumstellar Interactions

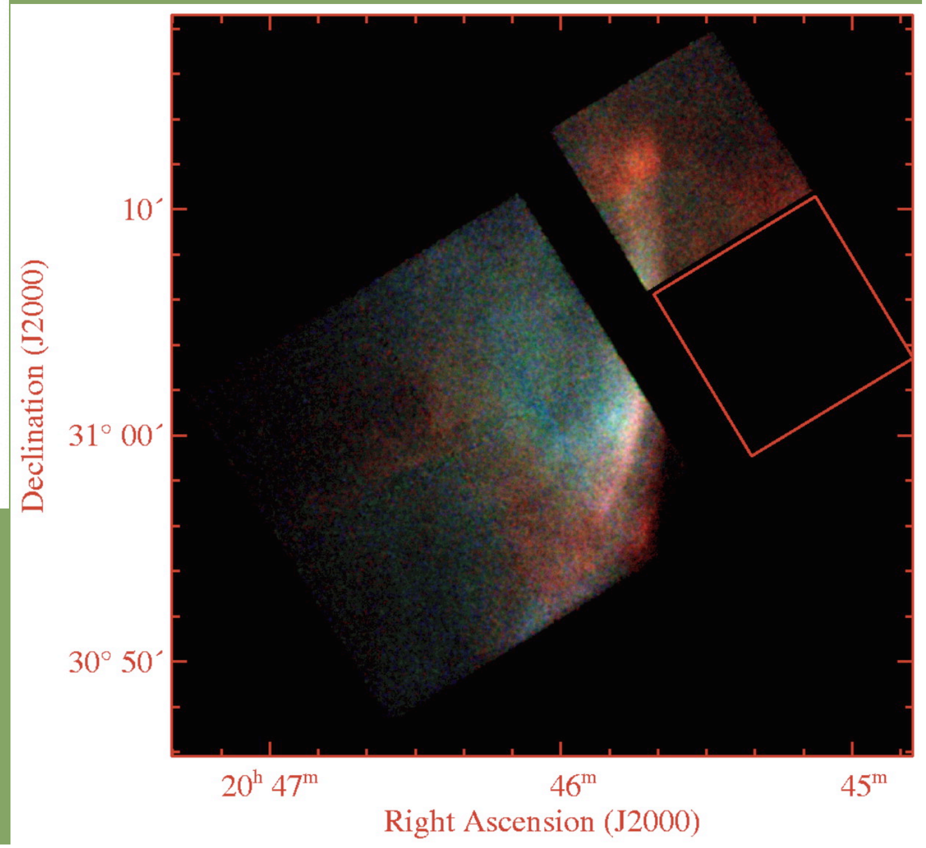


Cygnus Loop SNR

Evolving into a circumstellar cavity

Transmitted and reflected shocks at cavity wall

Infer density contrast, interaction timescale



Levenson et al. 2002

Some Pitfalls

Sufficient angular and spectral resolution are both important

Broadband spectral fits are seldom unique and unambiguous

Only a limited number of spectral parameters can be independently constrained.

elements abundances generally should not be fitted if you cannot see the corresponding lines
continua can often be fitted in numerous ways