Supernova Remnants

Explosion by core-collapse of massive stars (II, Ib/c) or thermonuclear instability in accreting C+O white dwarf (Ia)

~10^{51} ergs kinetic energy released per explosion

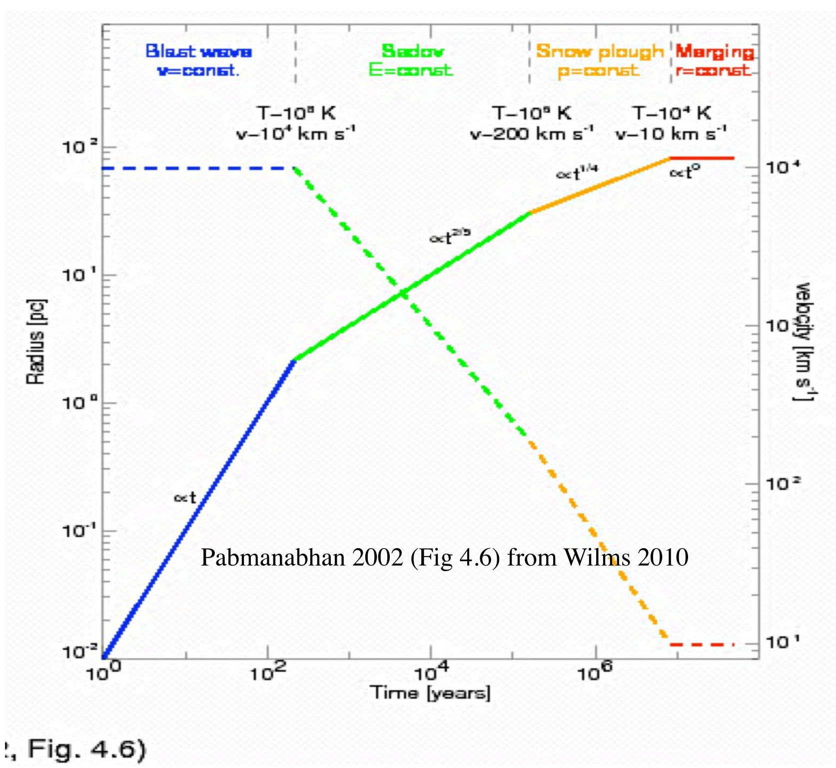
Forward shock heats and compresses interstellar medium, accelerates particles

Reverse shock heats ejecta starting from outermost layer inward as ejecta expand

Low gas densities, short ages of 100-10^4 yr (depends on gas density)
ionizing plasma: ionization timescale = $n_{electron}$ x t_{shock}

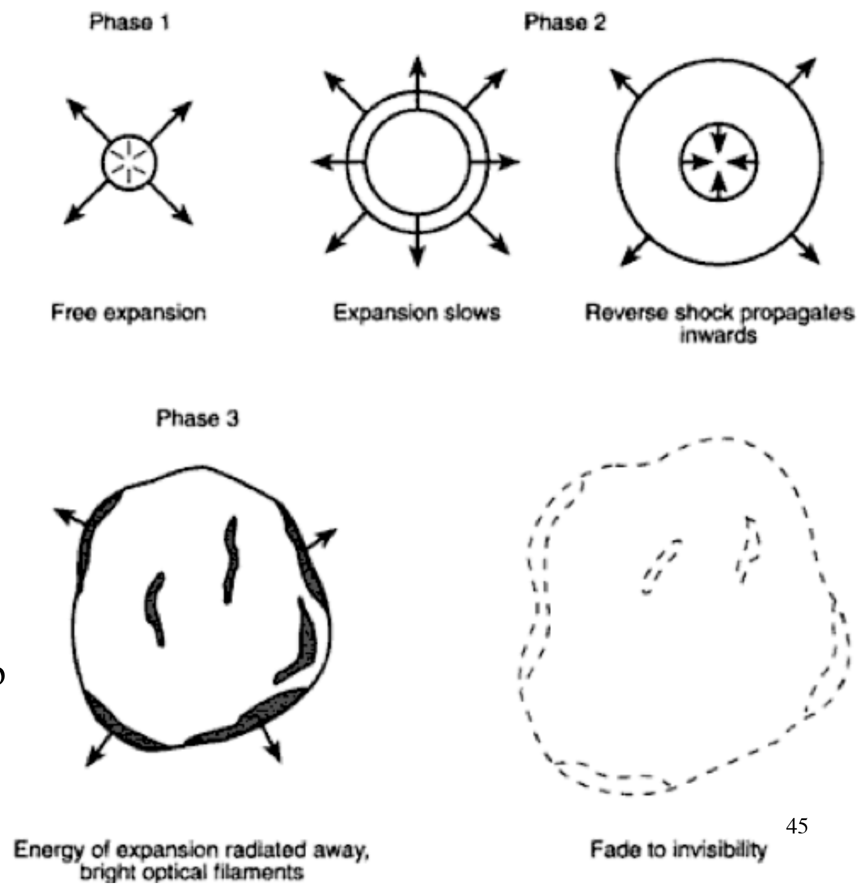
t_{fade}~1.9×10^6 yrs $E_{51}^{0.32}$ $n^{-0.37}(c_s/10\text{km/sec})^{-7/5}$

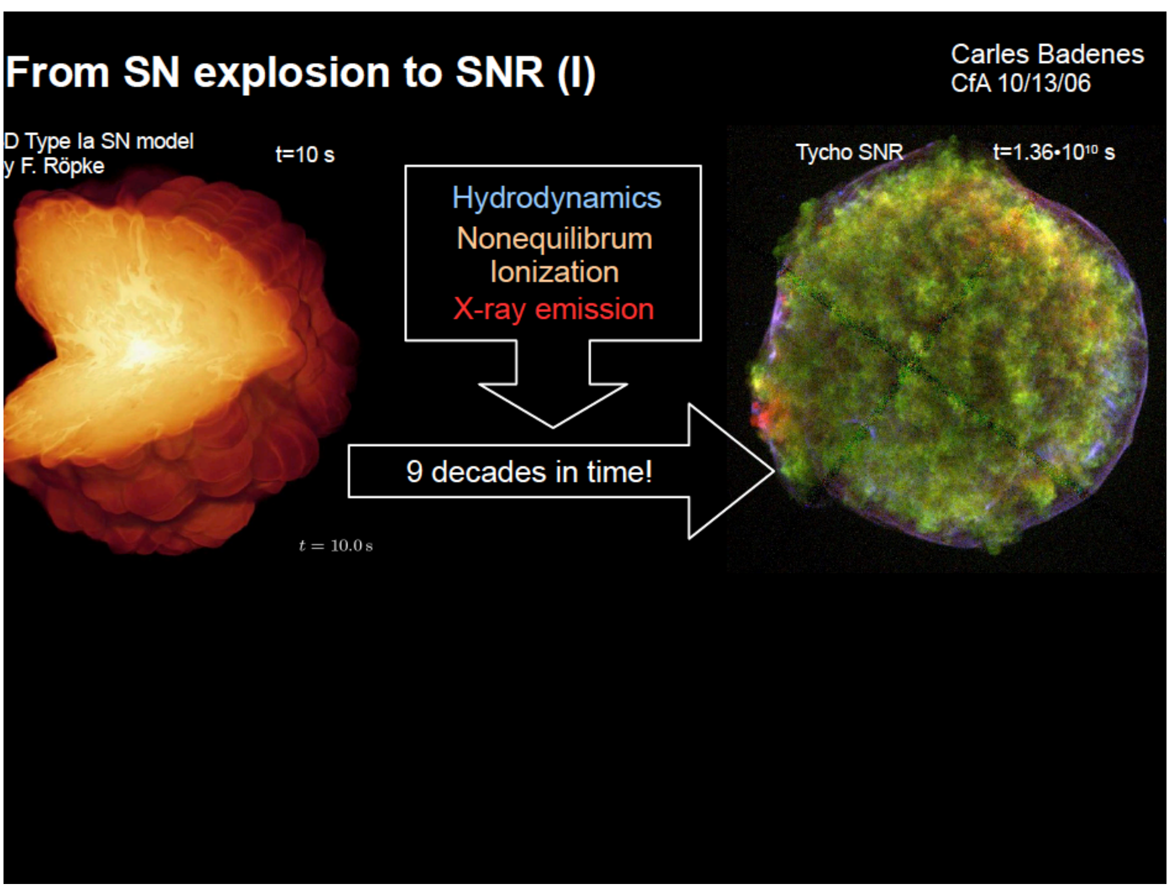
Draine



Pabmanabhan 2002 (Fig 4.6) from Wilms 2010

S. Safi-Harb


Phase 1
Phase 2
Free expansion
Expansion slows
Reverse shock propagates inwards
Phase 3
Energy of expansion radiated away, bright optical filaments
Fade to invisibility

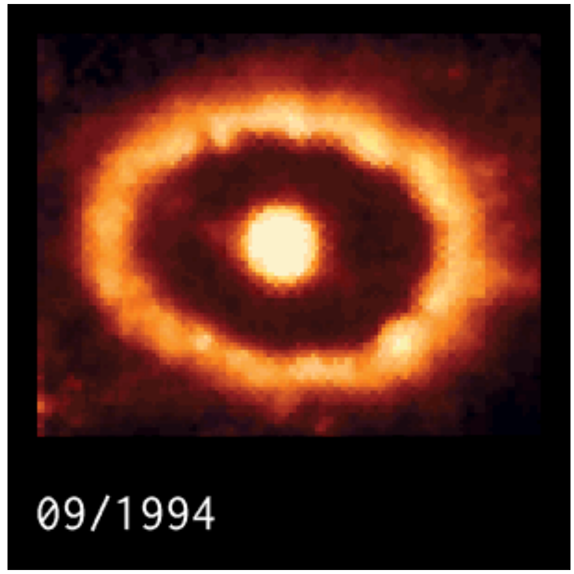

From SN explosion to SNR (I)
Carles Badenes
CfA 10/13/06
D Type Ia SN model
y F. Röpke
t=10 s
Hydrodynamics
Nonequilibrum
Ionization
X-ray emission
9 decades in time!
Tycho SNR
t=1.36•10¹⁰ s
t = 10.0 s

1987A

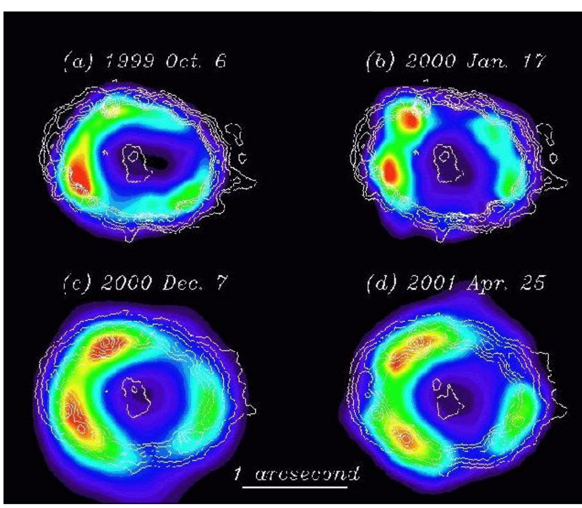
~24 neutrinos were detected ~12 hours before the optical light was detected-

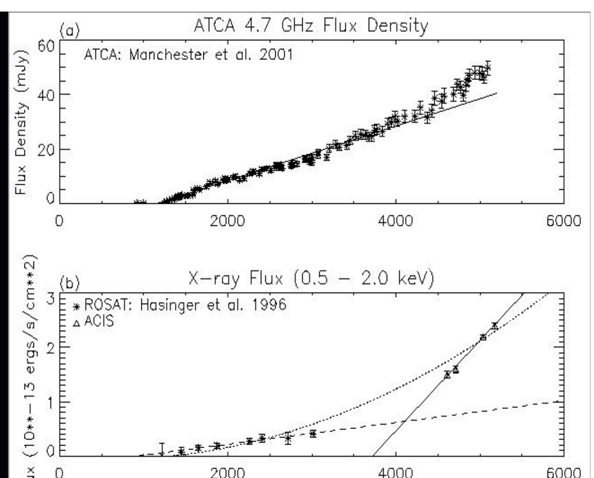
confirmation that neutrinos carry most of the energy and test of neutrino 'diffusion' theory

Direct detection of ^{56}Co γ-ray lines



SNR 1987A in Large Magellanic Cloud





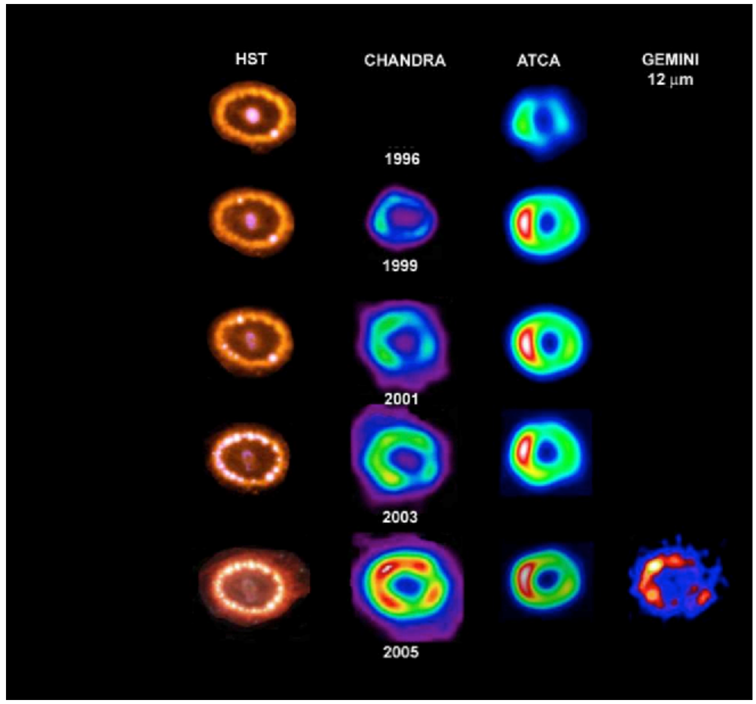
Park et al. 2002 , Burrows et al. 2001

days since explosion

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

Young SN remnants evolve rapidly

Some extragalactc SN have been followed for years

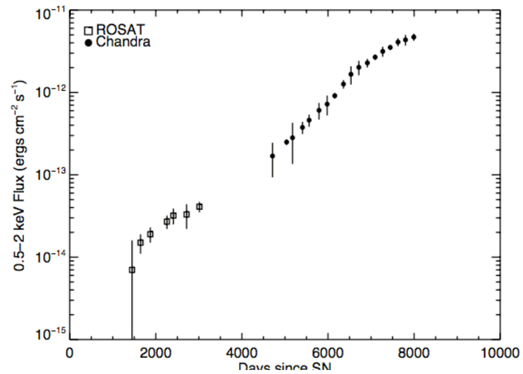


SN 1987A Through Time in Different Wave Bands

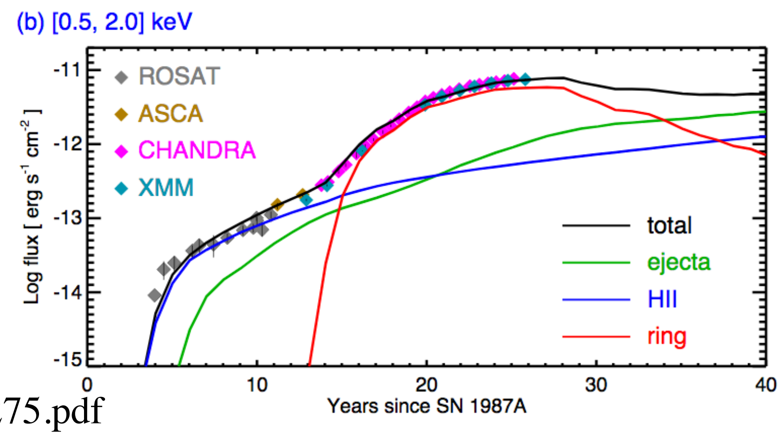
The Birth of a SNR

- See https://www.nasa.gov/feature/goddard/2017/the-dawn-of-a-new-era-for-supernova-1987a

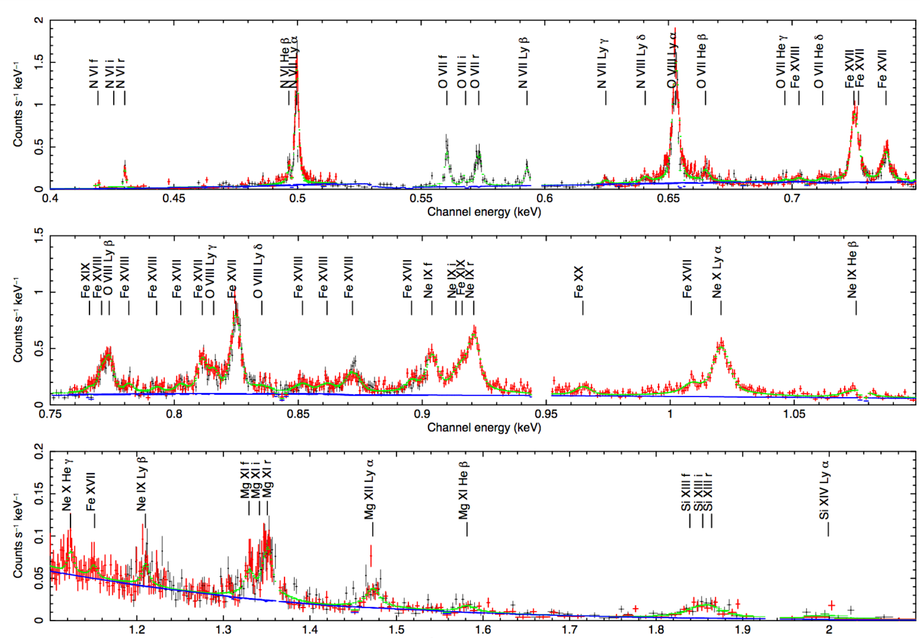
1987A - Latest X-ray Light Curves and Spectra



- See [Handbook of Supernovae]() pp 2181-2210 **The Physics of Supernova 1987A R. McCray**



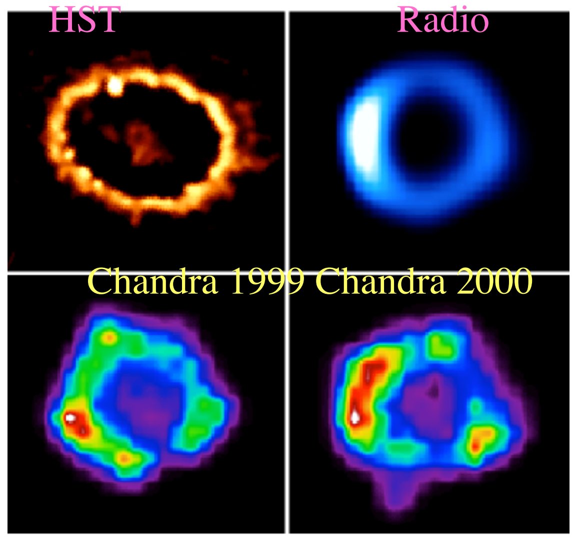
Orlando et al 1508.02275.pdf



- X-ray spectrum dominated by shocked gas with v_{shock}~550km/sec (rather slower than the optical emitting gas

SuperNova Remnants

- We distinguish between
  - SN explosions (the actual events and the next few years) and
  - Remnants - what happens over the next few thousand years.



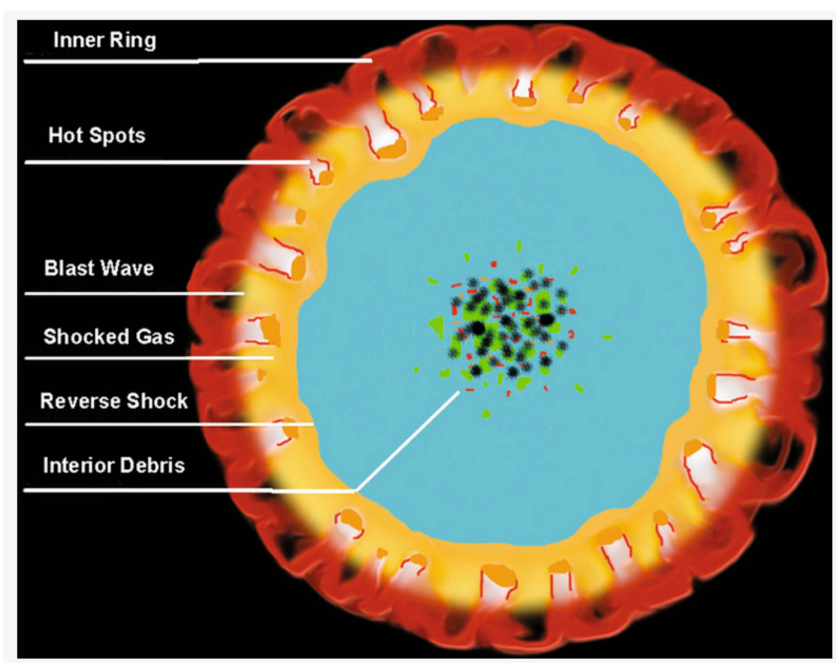
SN 1987A observed in 1999, 2000

SNRs enrich the ISM by dispersing material produced both during the star's life and at the moment of the SN event.

~2 per century for Milky Way (all types)- can directly study the chemical composition to constrain SN models

The Young SNR

The nucleosynthesis products in the interior debris are confined mostly within a sphere expanding with velocity ~ 2000 km s^{-1}



The blue-yellow interface represents the reverse shock , while the yellow annulus represents the X-ray-emitting gas, bounded on the outside by the blast wave . The white fingers represent protrusions of relatively dense gas.

SNII Explosions- Not Spherical Cows

Wongwathanarat et al. 2015) 20 and 15 M explosions

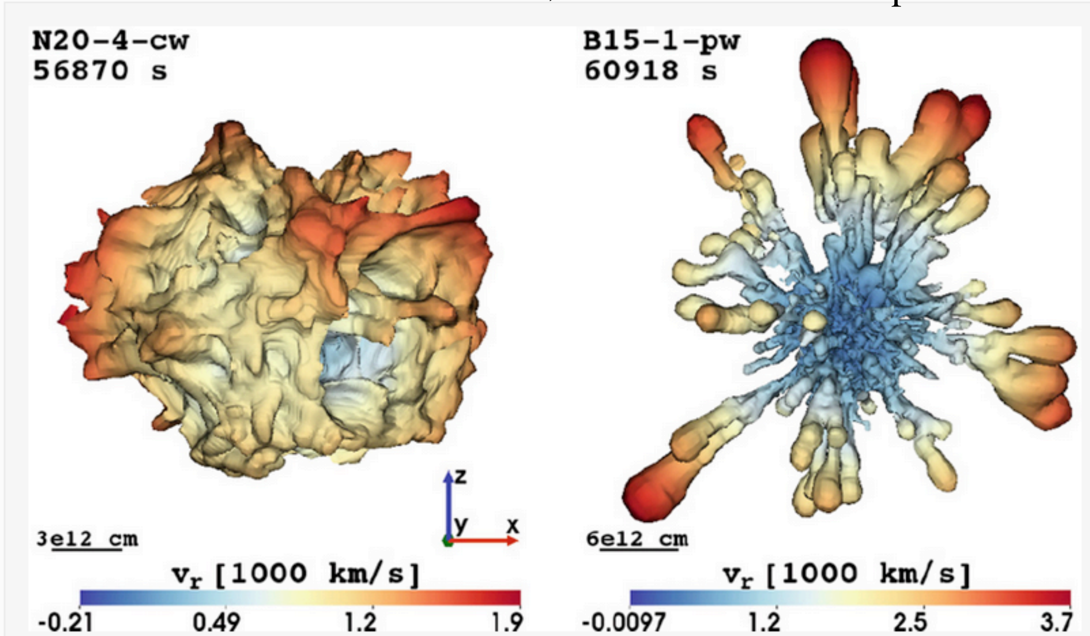


Fig. 3

3-D Structure

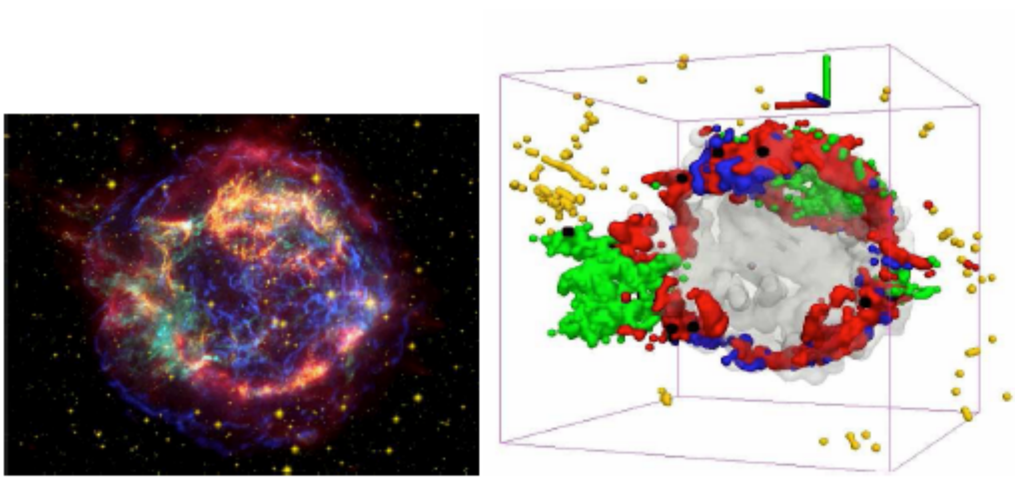


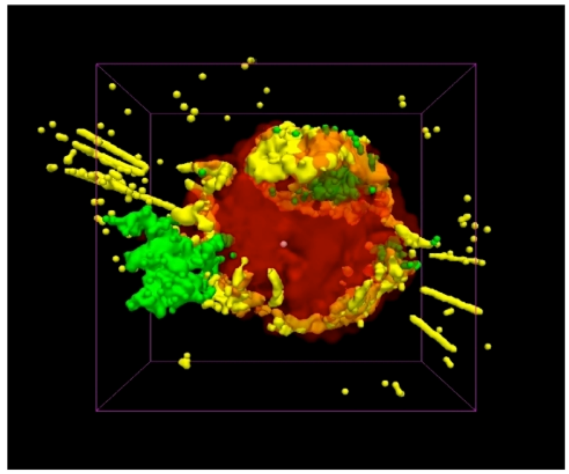
Fig. 2 Cas A present. Left: Composite view of Cas A in X-ray (*Chandra*, green & blue), visible (HST, yellow), and the IR (Spitzer, red); from *Chandra* Photo album, released June 2005. Right: A detailed 3D reconstruction of Cas A also in X-ray (black & green), optical (yellow), and IR (red, blue & gray.) Doppler shifts measured in X-ray and infrared lines provided the third dimension, from DeLaney et al. (2010).

Velocity data allows an inversion of the 2-D to 3-D structure

3-D View of Cas-A

- green is X-ray emitting Fe; yellow is X-ray, optical and infrared emitting Ar and Si;
- red is infrared emitting unshocked ejecta;
- the pink dot represents the compact object.

T. Delaney et al



SNRs are probes both of their progenitor star (and of their pre-supernova life) and of the medium into which they explode (the ISM)

They are also cosmic accelerators (cosmic rays).

Birth places of neutron stars and stellar mass black holes.

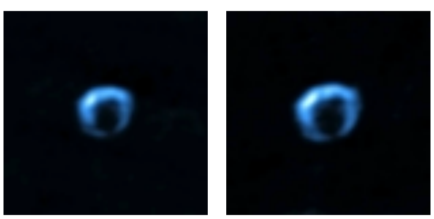
laboratories for study of magnetic fields, shock physics, jets, winds, nuclear physics etc

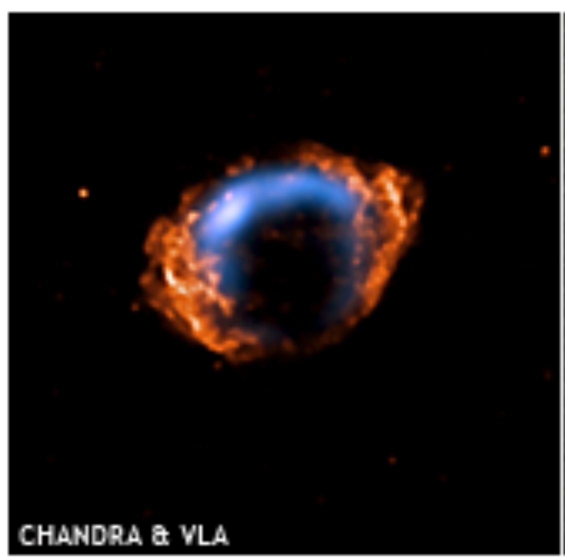
- SNR evolution (and their appearance now) depends on many factors:
  - age
  - environment (density)
  - total energy of the explosion
  - progenitor star (mass, type of SN associated..)

SNR Types

- Shell-like – thermal
  - Young objects whose global X-ray emission is dominated by emission from ejecta
    - Cas A, Tycho
  - Old objects dominated by thermal emission at the primary shock
    - Cygnus Loop, PKS1209-52
- Shell-like – non-thermal
  - Young SNRs dominated by non-thermal emission, often bright VHE gamma ray sources
    - RX1730-3946, Vela Jr, G1.9+0.3, SN1006
- Pulsar wind nebulae
  - Centrally peaked emission from non-thermal radiation due to electrons powered by a rapidly rotating neutron star
    - Crab Nebula, 3C 58
- Mixed morphology
  - Centrally peaked objects (sometimes with a shell as well) dominated by thermal emission
    - May also have some non thermal emission due to a pulsar
  - Heterogeneous set of old and young objects

G1.9+0.3 Most Recent SN in MW

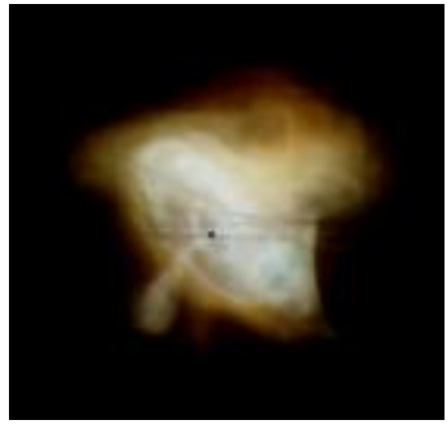


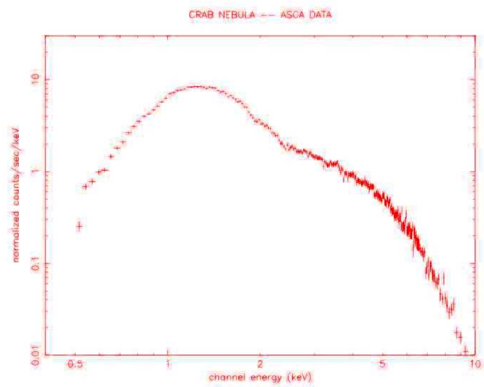


- 2 radio images separated by 13 years showing expansion and implied explosion epoch 140 years ago
- Not noticed because near galactic center, region of high extinction
- A simple uniform-expansion model describes the data well, expansion rate of 0.642% ± 0.049% yr-1 Without deceleration, the remnant age 156 ± 11 yr,
- G1.9+0.3 is the only Galactic SNR increasing in flux, with implications for the physics of electron acceleration in shock waves.

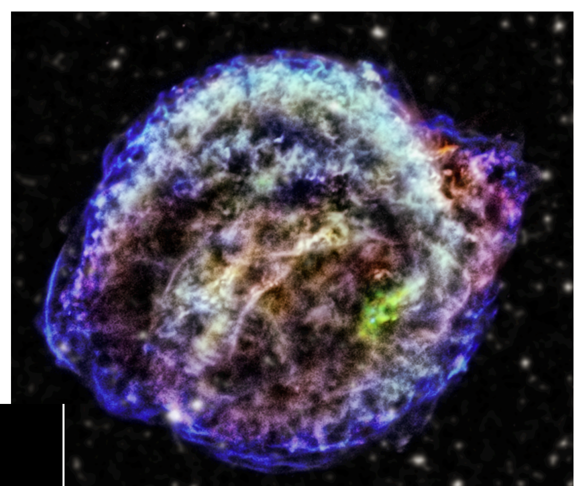
Non-Thermal Remnants

- Sometimes the explosion does not seem to produce lots of hot gas and instead one detects synchrotron emission from relativistic particles produced by a central Neutron star
  - these are called *plerions* or 'Crab-like' SNR.
  - in 'thermal' remnants there can be also exist synchrotron emission from shock accelerated electrons in other SNR

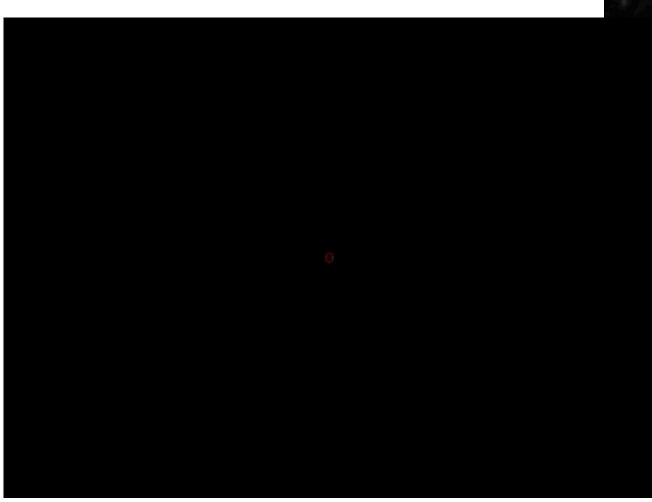




- Kepler SNR- remnant of a type Ia
- Chandra analysis indicates that the Kepler supernova was likely triggered by an interaction between a white dwarf and a red giant star.

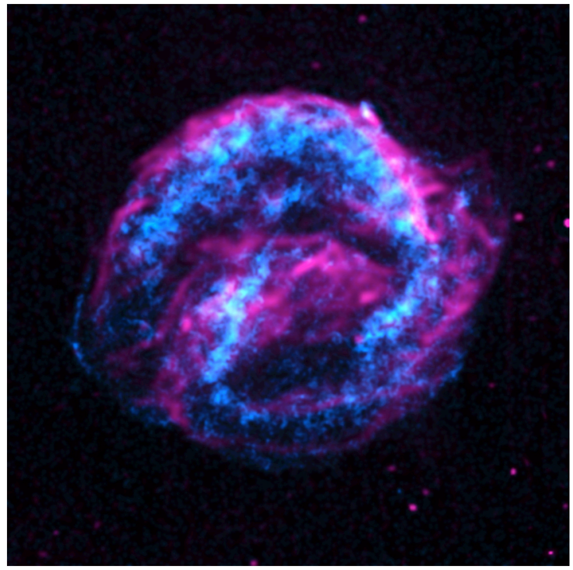


x-ray and optical image



Kepler SNR

- **Fe Emission in the x-ray band in blue**, **IR emission due to dust in pink.**
- Notice strong asymmetry in Fe emission



Kepler Line Images

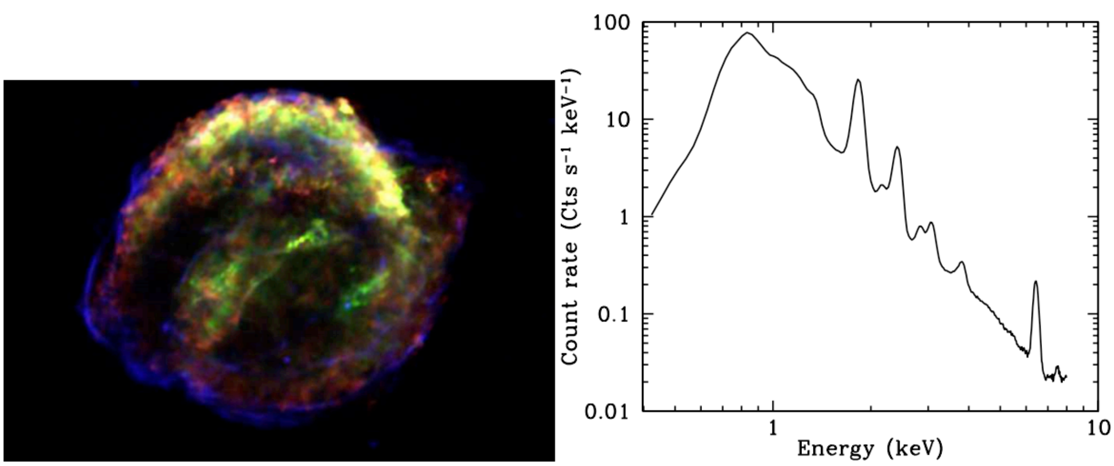


Figure 24: Left: *Chandra* image of Kepler's SNR, with red indicating Si-K α emission (1.75-1.95 keV), L emission (0.8-1.6 keV), and blue continuum emission (4-6 keV). The image is based on a deep, 750 ks,

- Vink 2012

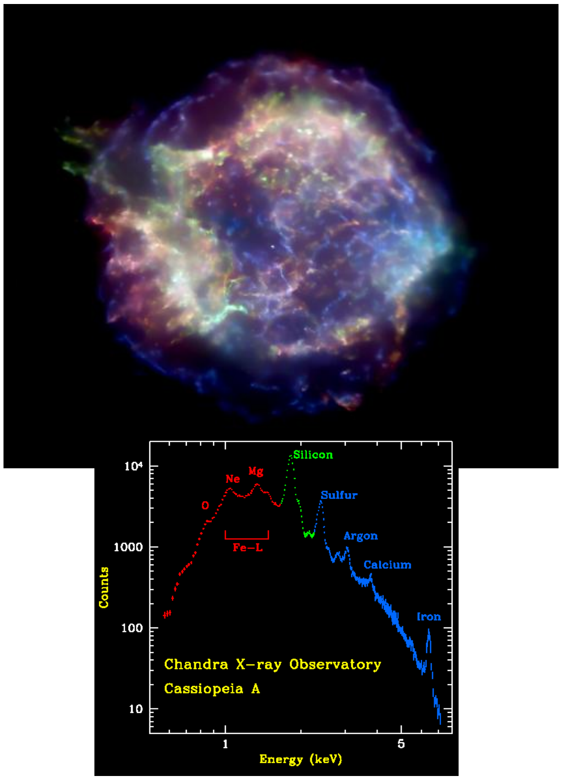
X-ray Emission from Supernova Remnants

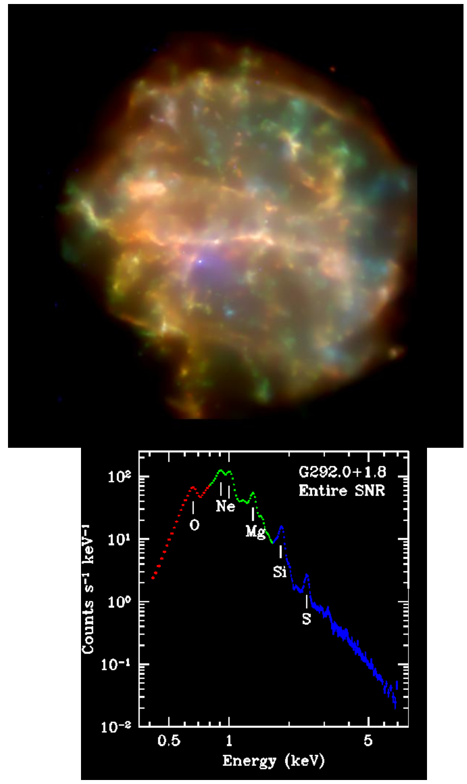
Thermal Emission
- characterized by electron temperature, ionization timescale, element abundances
- primarily bremsstrahlung continuum
- collisionally excited emission lines

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)
  - some SNR are dominated by NT emission (Crab-like, plerions)

In our Galaxy there are~300 identified SNRs

~ 8% detected in the TeV range
~ 10% in the GeV range
~ 30% in optical wavelengths
~ 40% in X-rays
~ 95 % in radio.

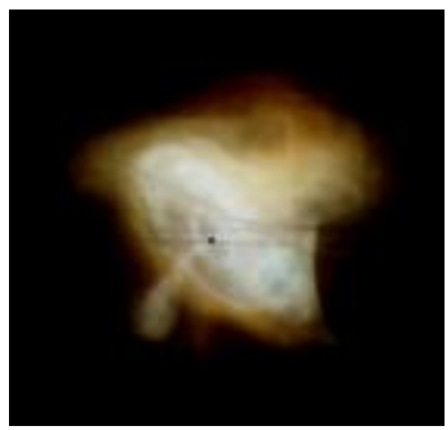


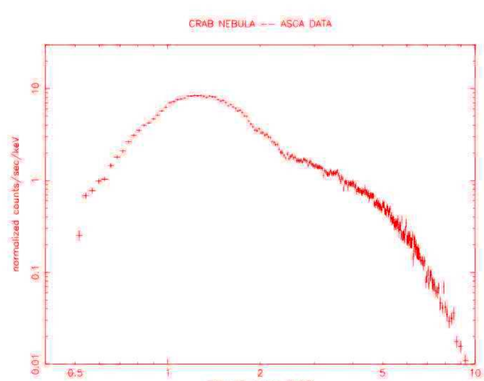


- Type Ia produce mainly Fe -- low O/Fe ratio.
- Type II produces: mainly 0 -- high O/Fe ratio

Non-Thermal Remnants

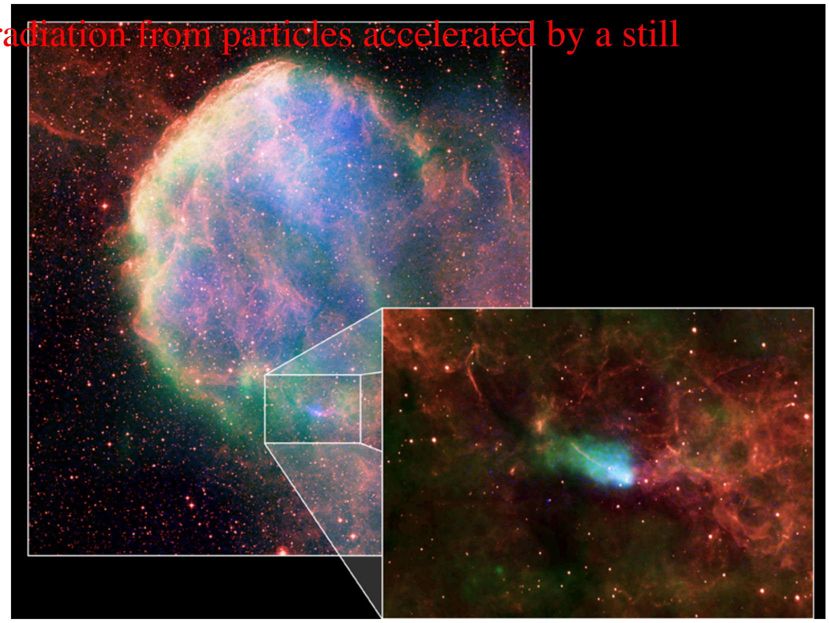
- Sometimes the explosion does not seem to produce lots of hot gas and instead one detects synchrotron emission from relativistic particles produced by a central Neutron star
  - these are called plerions or 'Crab-like' SNR.
  - in 'thermal' remnants there can be synchrotron emission from shock accelerated electrons in other SNR

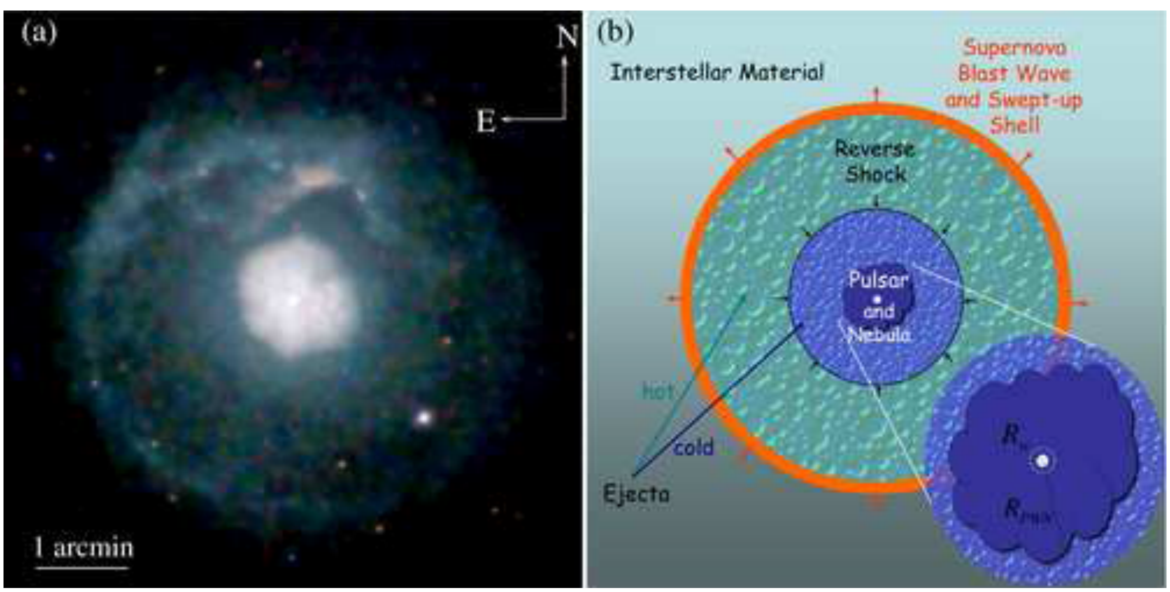




Combining Bremmstrahlung and Synchrotron Radiation

- In some supernova remnants one sees both processes at work
  - Bremmstrahlung from electrons that are shock heated by the SN blast wave +line emission
  - Synchrotron radiation from particles accelerated by a still active pulsar





- Composite SNR G21.5- 0.9 (Matheson & Safi-Harb 2005).

3 phases in SNR's life.

- Free expansion (less than 200-300 years)
- Adiabatic or "Taylor-Sedov" phase (about 20,000 years)
- Radiative or Snow-plow phase (up to 500,000 years)

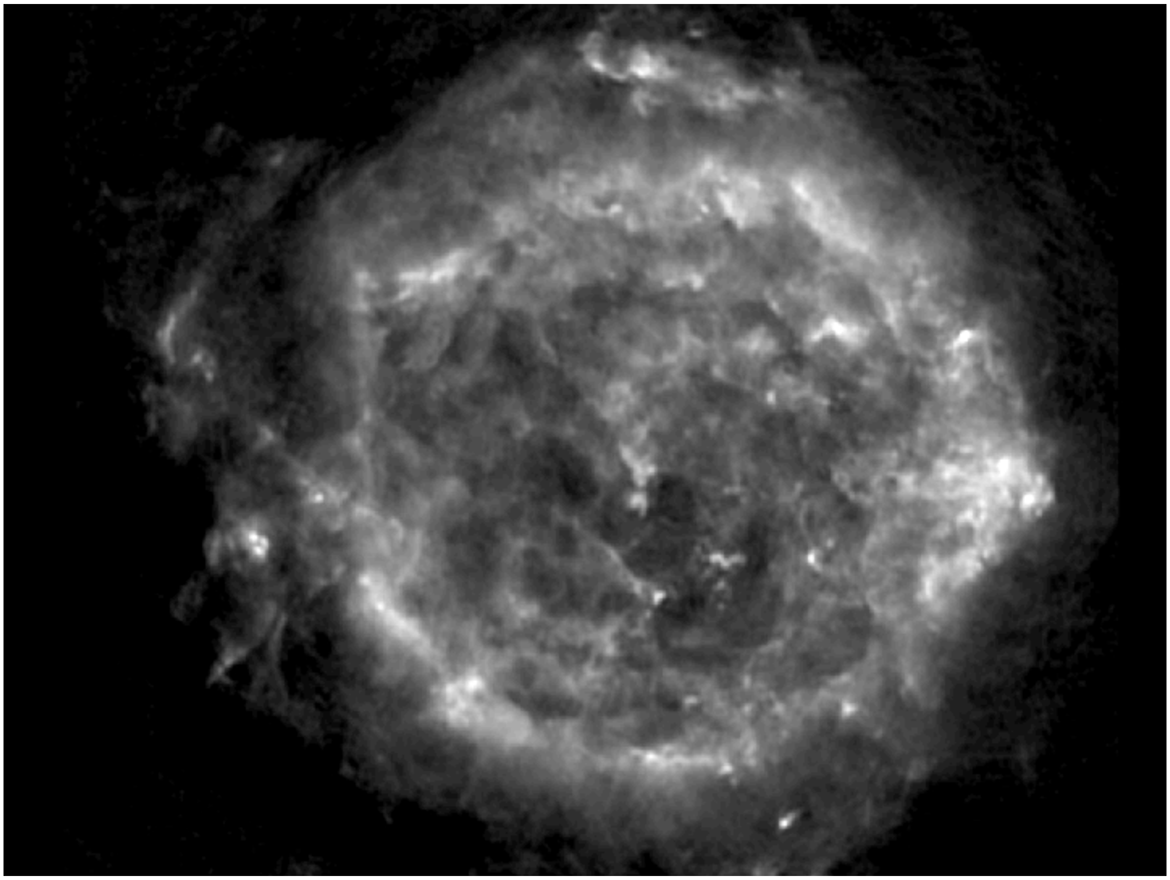
and then … Merge with the ISM

Remnant Evolution

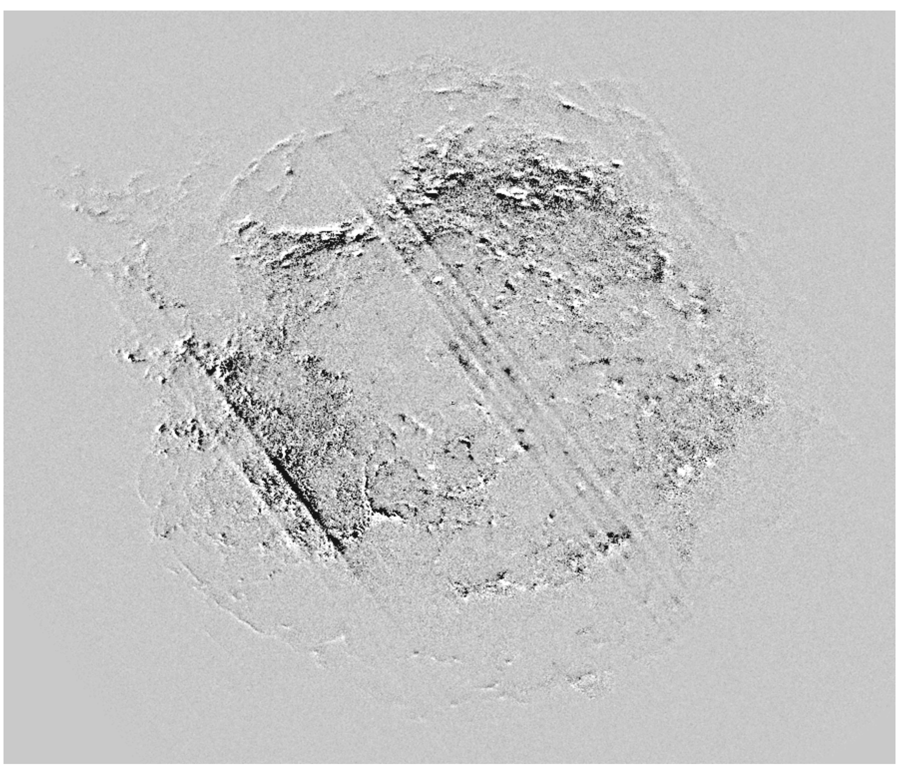
Free Expansion
Ejecta expand without deceleration r~t (see movie Rudnick et al., 1996, BAAS, 188.7403.) - Core collapse SN have initial velocities of ~5000km/sec and several $M_\odot$ of ejecta , SN Ia ~10,000 km/sec, ~1 $M_\odot$

Adiabatic (Sedov-Taylor, or "atomic bomb")
Ejecta are decelerated by a roughly equal mass of ISM- $r \sim t^{2/5}$
Energy is conserved-(Cooling timescales are much longer than dynamical timescales, so this phase is essentially adiabatic e.g. net heat transfer is zero).
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- typically occurs when shock velocities vs drop to around 200 km/sec



Cas-A Difference of X-ray Images Taken 2 Years Apart Delaney e al 2005



Reminder....Useful Equations for the 3 Phases

$$R = vt,$$
$$v = (2E_0/M_{ej})^{0.5}$$
Free Expansion

Sedov-Taylor

$V_s=(2/5)R_s/t=$
$5000 km/s\ (r/2pc)\ E^{1/2}_{51} n^{-1/2}$

$R_s \sim 0.3 pc\ E^{1/5}_{51} n^{-1/5} t_{yr}^{2/5}$

$T \sim 10^6\ E^{2/5}_{51} n^{-2/5} t_{30000yr}^{-6/5}$

Radiative Phase

$$T_{rad} = 1.4 \times 10^{12} \left(\frac{E_{51}}{n_H}\right)^{1/3} s \approx 44{,}600 \left(\frac{E_{51}}{n_H}\right)^{1/3} yr,$$

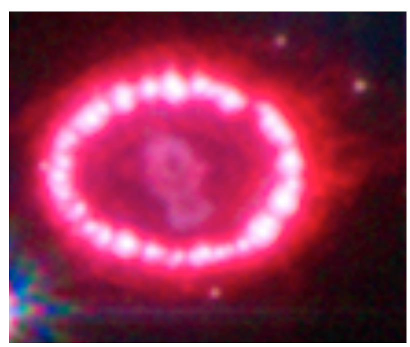
$$R_{rad} = 7.0 \times 10^{19} \left(\frac{E_{51}}{n_H}\right)^{1/3} cm \approx 23 \left(\frac{E_{51}}{n_H}\right)^{1/3} pc,$$

Free expansion phase

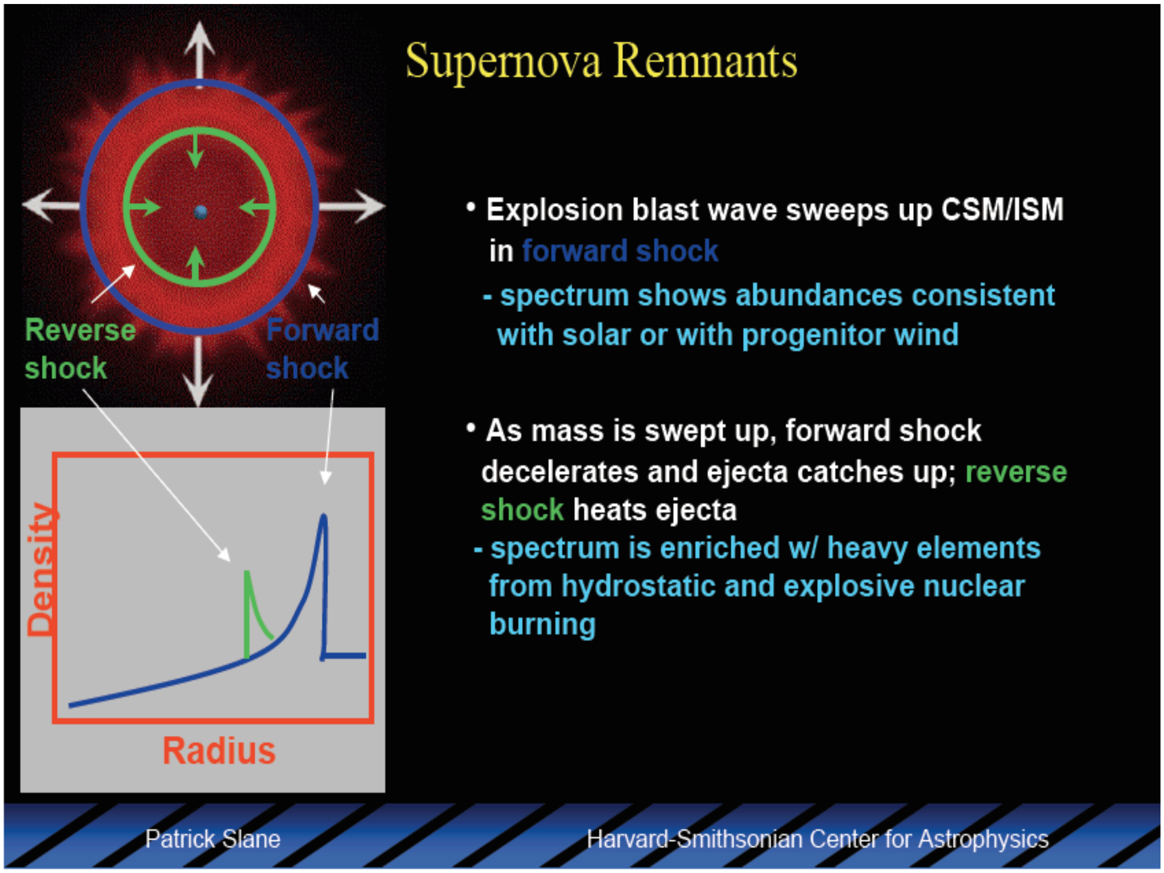
- Independent of the nature of the SN explosion
- No deceleration
- Evolution only depends on E_o the initial energy.
- Velocity of ejected shell ~ 10^4 km s^{-1}
- Mass swept-up negligible until $M_{sN} \sim M_{eje} \sim 1\ M_\odot$

===> R_s = 250 yrs $M_{eje}^{5/6}\ n_1^{-1/3}\ E_{51}^{-1/2}$

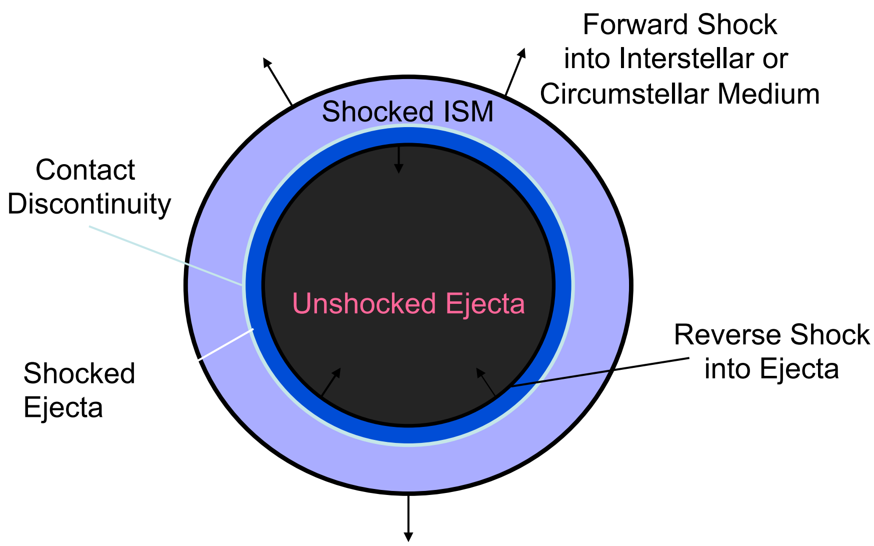
SNR enters then its Adiabatic Phase



1987A HST in 2010

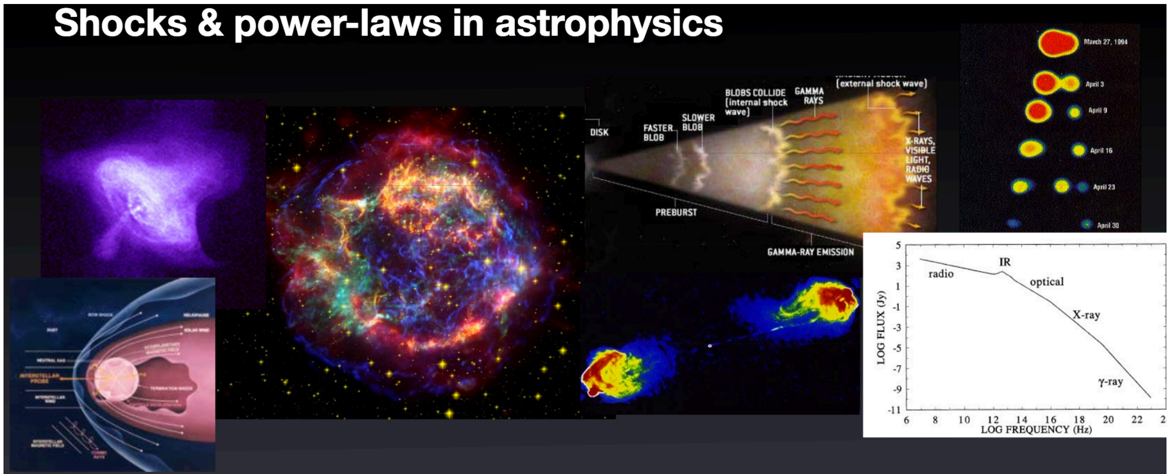


Supernova Remnant Cartoon



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

Shocks & power-laws in astrophysics



Astrophysical shocks are typically collisionless (mfp >> shock scales).
Many astrophysical shocks are inferred to:

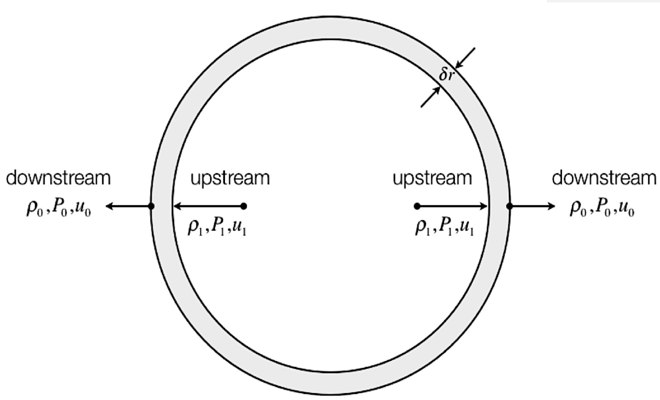
1) accelerate particles to power-laws
2) amplify magnetic fields
3) exchange energy between electrons and ions

Spitkovsky

How do they do this? Mechanisms, efficiencies, conditions?…

Shock Jump Conditions

- Conservation of Mass $$\rho u = constant$$
- Conservation of Momentum $$P + \rho u^2 = constant$$
- Conservation of Energy $$\frac{u^2}{2} + \frac{5P}{2\rho} = constant$$



assuming: no B, no E-losses due to Cosmic Rays e.g., t-independent adiabatic flow and mono-atomic gas
S. Safi-Harb

Shock Solutions

$$\rho_1 = \frac{\gamma+1}{\gamma-1}\rho_0$$
$$u_1 = \frac{\gamma-1}{\gamma+1}u_0$$
$$P_1 = \frac{2\rho_0 u_0^2}{\gamma+1}$$

$$\gamma = 5/3$$

$$\rho_1 = 4\rho_0$$
$$u_1 = \frac{1}{4}u_0$$
$$P_1 = \frac{3}{4}\rho_0 u_0^2$$

$$v_1 = \frac{3}{4}V_s$$

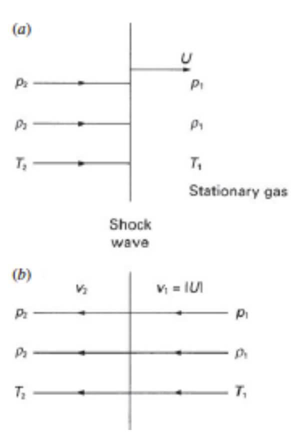
$$kT_1 = kT_s = \frac{3}{16}\mu m_H \times V_s^2$$

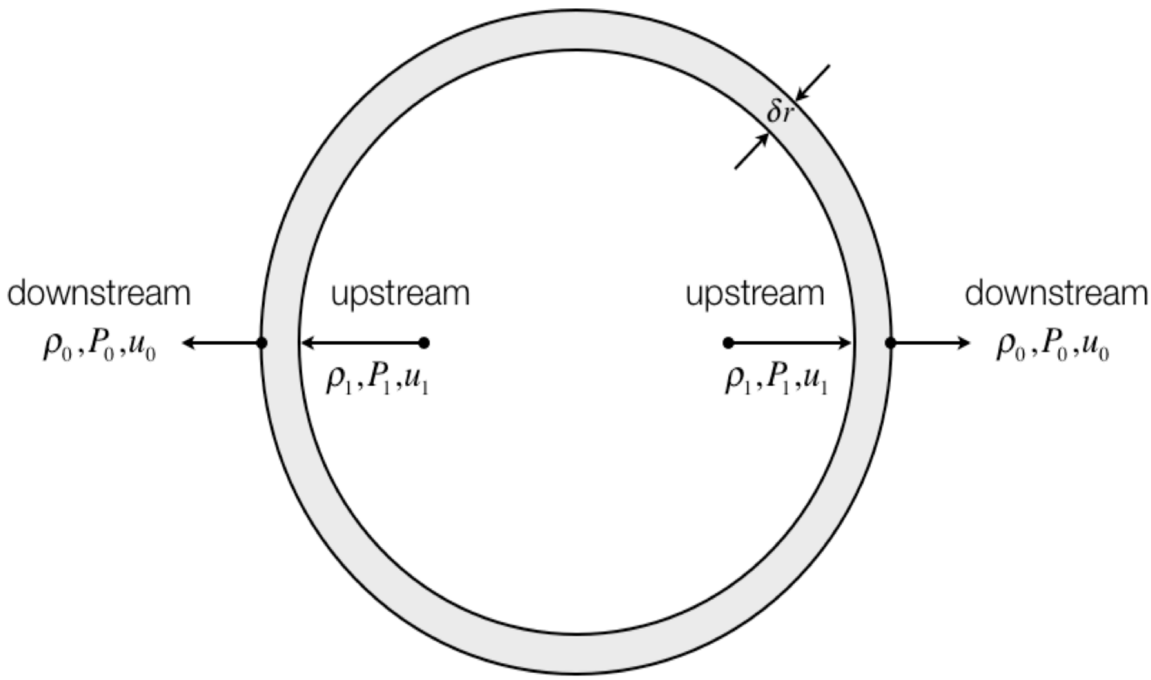
$$T_s\ (K)\ \sim 1.13\times 10^5 (\frac{V_s}{10^7})^2$$

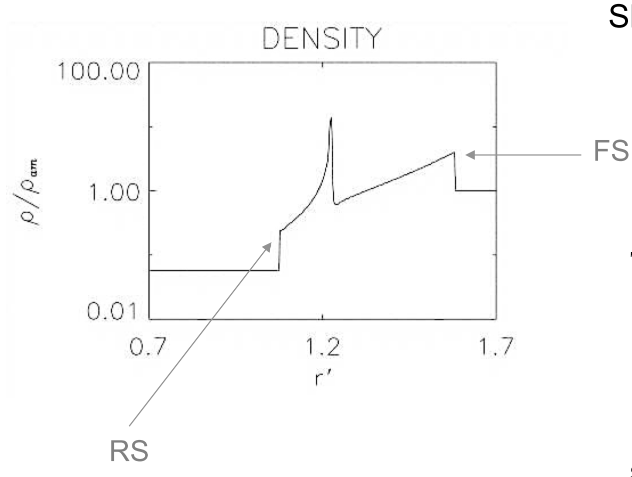
Shock Physics Longair 3.14

In a frame of reference in which the shock is stationary, the gas entering the shock from upstream has density, ϱ_1, velocity, u_1, pressure, $P_1 = nkT_1$, and internal energy density, ϵ_1. The corresponding parameters describing the downstream flow are ϱ_2, u_2, P_2, and ϵ_2.
The internal energy density of the gas is related to its density and pressure by $\epsilon = P/[(\gamma - 1)\varrho]$; **γ=5/3** for a monoatomic gas

Using conservation of mass, momentum and energy (Rankine-Hugoniot eqs) gives
$\rho_2/\rho_1 = u_1/u_2 = [\gamma+1]/(\gamma-1) + (2/M^2)$;
M= Mach number of shock as
M=v/c where
c is the speed of sound
goes to infinity $\rho_2 = 4\rho_1$,







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) coupled through the structure of turbulence in shocks and acceleration

Collisions do mediate ionizations and excitations in the shocked gas

Shocks in SNRs transform bulk energy of ejecta into thermal energy of the gas and nonthermal energy associated with magnetic fields and high energy particles!

They occur because the expanding ejecta are moving at speeds much greater than the sound speed of the pre-shock gas

Shock structure is affected by nature of the pre-shock gas, how magnetic fields evolve in the shock and how much energy is lost to cosmic rays!

Shocks in SNRs are said to be collisionless because Coulomb collisions take too long to produce the shocks that are observed

$$\sigma_{Coulomb} = \frac{4\pi\, Z_1^2 Z_2^2\, e^4}{m_{reduced}^2 v^4} = 10^{-20} cm^2\ (proton - proton)$$

$$\tau_{Coulomb} = \frac{1}{n\sigma_{Coulomb} v} = 35000\ n^{-1}\ v_{1000\ km}^{-1}\ yrs$$

Shock Physics Longair 11.3

In limit of strong shocks the temperature and pressure can become very large. speed of the ejecta can be ~5000km/s
In the shock front the undisturbed gas is both heated and accelerated as it passes through the shock front mediated by their atomic or molecular viscosities.
The acceleration and heating of the gas takes place over a physical scale of the order of a few mean free paths of the atoms, molecules or ions of the gas.
the shock front is expected to be narrow and the heating takes place over this short distance.

$$\frac{p_2}{p_1} = \frac{2\gamma M_1^2}{(\gamma+1)},$$

$$\frac{\rho_2}{\rho_1} = \frac{(\gamma+1)}{(\gamma-1)},$$

$$\frac{T_2}{T_1} = \frac{2\gamma(\gamma-1)M_1^2}{(\gamma+1)^2}$$

$$kT_2 == \frac{1}{4}\left(1-\frac{1}{4}\right)\mu m_p v_o^2 = \frac{3}{16}\mu m_p v_o^2$$

$$T_2 = \sim 1.36\ 10^7 K \left(\frac{v_1}{1000\ km\ s^{-1}}\right)^2 = 1.17\ keV\ \left(\frac{v_1}{1000\ km\ s^{-1}}\right)^2$$

The Shock

- A key ingredient in SNR dynamics is the strong (high Mach number) shock which is "collisionless"
- the effect of the shock is carried out through electric and magnetic fields generated collectively by the plasma rather than through discrete particle–particle collisions
- the shock system is given by the synonymous terms "adiabatic" and "non-radiative" to indicate that no significant energy leaves the system in this phase
- a "radiative" shock describes the case where significant, catastrophic cooling takes place through emission of photons

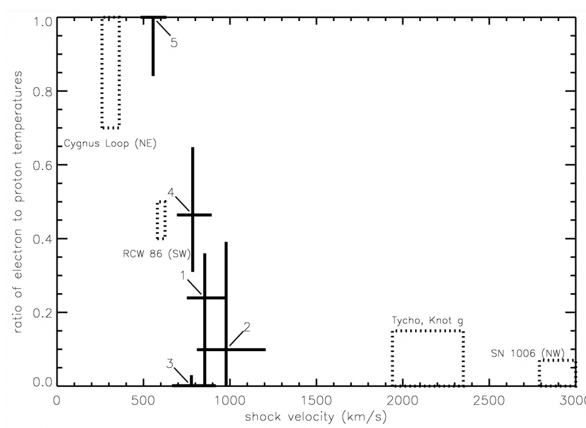
Electron Heating at SNR Shocks
Compare T_e to T_p

Temperatures behind shock are proportional to mass

$kT_{i,e} \sim m_{i,e} v_{sh}^2$

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

Shocked Plasma takes time to come into equilibrium

- particle (“Coulomb”) collisions in the post-shock plasma bring the temperature of all species, including the free electrons, to an equilibrium value: $kT = 3/16 \mu m_p v_s^2$

- However it takes time for the system to come into equilibrium and for a long time it is in non-equilibrium ionization (NEI)

  $\tau \sim n_e t \sim 3 \times 10^{12} cm^{-3} s$; when $\tau > 10^{12}$ it is in approx equilibrium

if the plasma has been shocked recently or is of low density it will not be in equilibrium

Shocked Plasma takes time to come into equilibrium

- Line ratios of He-like ions and total He-like line flux are especially sensitive to non-equilibrium effects
- In the graph the ratio of forbidden to resonance OVII line strength is plotted vs the ratio of the total OVIII/OVII ratio as a function of electron temperature T_e and $n_e t$

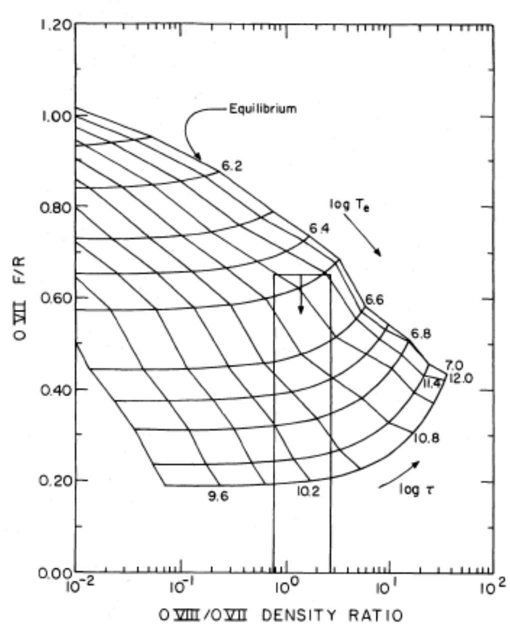
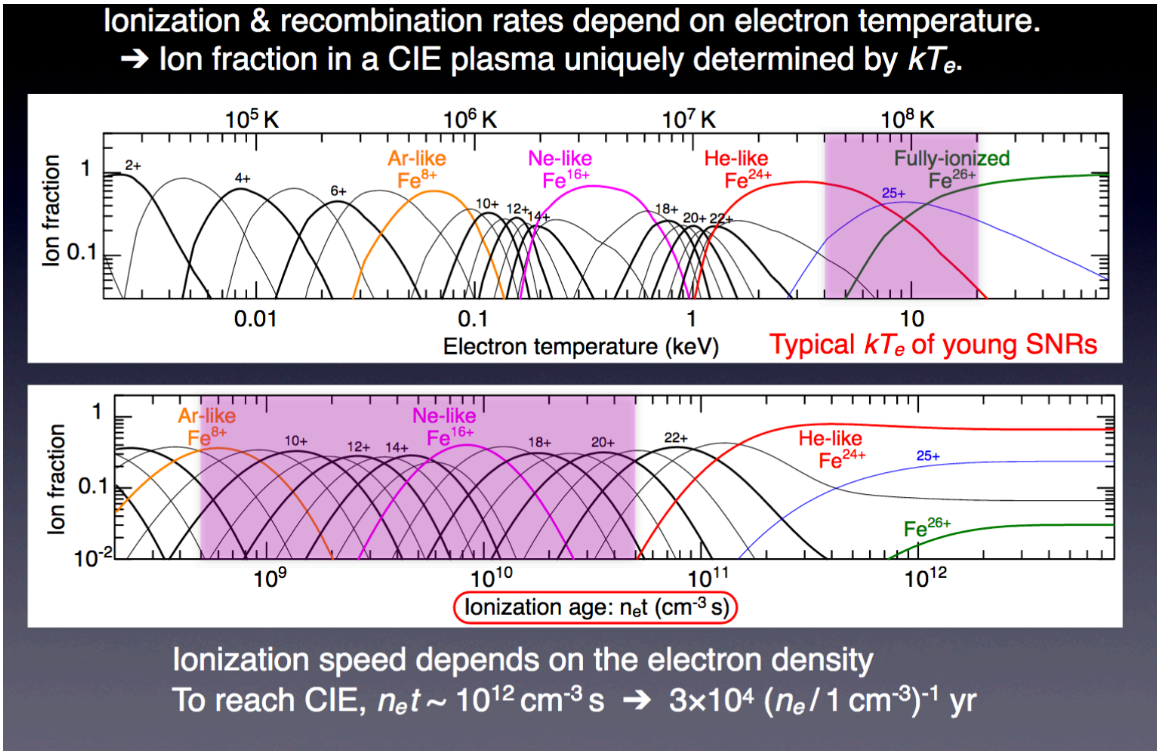


FIG. 3.—The results of our ionization nonequilibrium model (see text). The

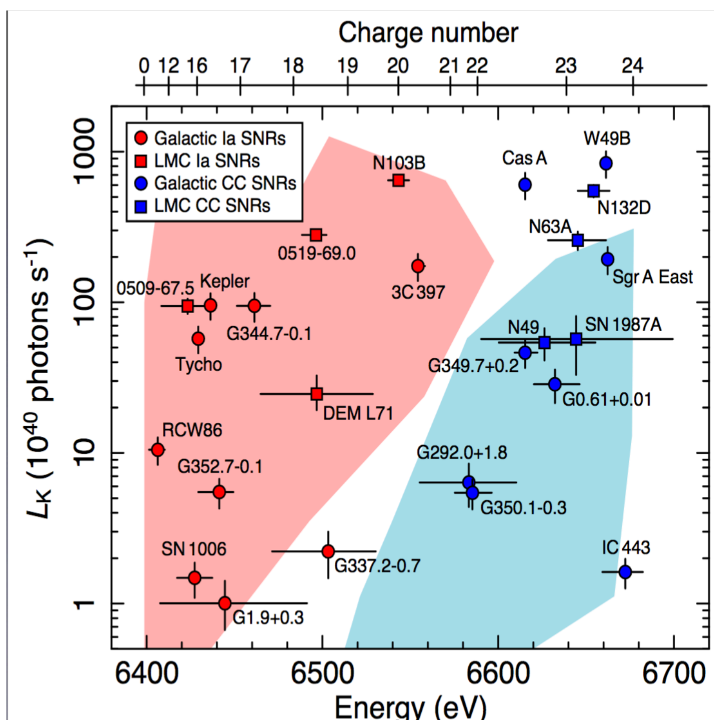


- H. Yamaguchi 2015

NEI Diagnostic and SNR Type

Ionization age $\propto n_e t$
Luminosity in Fe K line $\propto n_e N_{Fe}$
Type Ia = uniform ambient medium
CC = dense CSM

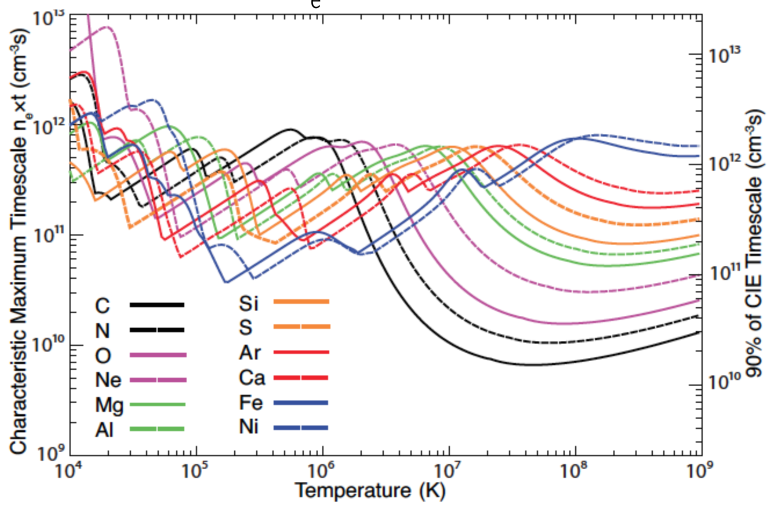
H. Yamaguchi 2015



Yamaguchi+2014a, ApJL, 785, L27

- Timescale to reach equilibrium depends on ion and temperature- solution of coupled differential equations.

Time scale to achieve 'equilbrium' for a given ion as a function of temperature- while the is some range from ion to ion most have $n_e t \sim 10^{12}$

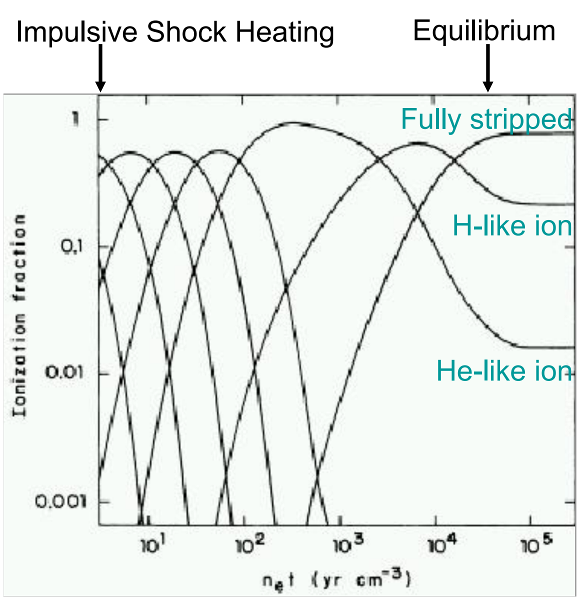


G. 1.— [Left axis] Density-weighted timescales (in units of cm^{-3} s) for C, N, O, Ne, Mg, Al, S, Si, Ar, Ca, Fe, and Ni to achieve one ding (e^{-1}) towards ionization equilibrium in a constant temperature plasma. [Right axis] Density-weighted timescale for all ions to be in 10% of their equilibrium value.

Smith and Hughes 2010

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 $n_e t \sim 10^{12}$ 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

Sedov-Taylor phase

This solution is the limit when the swept-up mass exceeds the SN ejecta mass -the SNR evolution retains only
vestiges of the initial ejecta mass and its distribution.

The key word here is SELF SIMILAR *(solutions can be scaled from solutions elsewhere)*

===> $f(r, t)$ becomes $f(r/r_{ref}) * f(r_{ref})$

(skipping the equations) $R_s = 12.4$ pc $(KE_{51}/n_1)^{1/5}\ t_4^{\ 2/5}$

$t = 390$ yr $R_s\ T_{meas}^{\ -1/2}$

In the Sedov-Taylor model one expects thermal emission coming from a thin shell behind the blast wave. As the shock expends the pressure drops between the shock wave and the material ejected.

- Forward shock into the ISM- is a 'contact discontinuity'- outside of this the ISM does not yet 'know' about the SN blast wave

- Reverse shock- information about the interaction with the ISM travels backwards into the SN ejecta
- Shell like remnants
- **Shell velocity much higher than sound speed in ISM, so shock front of radius R forms.**

- If the density (gm/cm^3) in the ISM/circumstellar gas is ρ_{ism}
- then the radius of the shock when it has swept up an equal mass to the eject M_{ejecta} is simply
- $r_1=2pc(M_{ejecta}/M_{\odot})^{1/3} (\rho_{ism}/10^{-24} gm/cm^3)^{-1/3}$

- to get an estimate of the time this occurs
  - assume that the shock has not slowed down and the total input energy remains the same (radiation losses are small) and travels at a velocity $v_{ejecta}=(v_{ejecta}/10^4$ km/sec) to get

$t_1=r_1/(v_{ejecta}/10^4 \text{ km/sec}) =200 \text{ yr}(E_{51})^{-1/2}(M_{ejecta}/M_{\odot})^{5/6}(r_{ism}/10^{-24} gm/cm^3)^{-1/3}$

- To transform variables total energy $E=1/2M_{ejecta}v^2\sim r^3\rho_{ism}v^2$ to get $r\sim(E/\rho_{ism})^{1/5} t^{2/5}$

Limit of Strong Shocks

- Ratio of temperatures behind and in front of the shock is related to the Mach speed, $\mathcal{M}$, of the shock (shock speed/sound speed in gas)

- $T_2/T_1=(2\gamma(\gamma-1)\mathcal{M}^2)/(\gamma-1)^2=5/16\mathcal{M}^2$ if the adiabatic index $\gamma=5/3$ (ideal gas)

Radiative/Snow plough phase

T drops as a steep function of radius

===> at some point, T is below T_{recomb} ~ 1 keV- the cooling function increases steeply and the gas recombines rapidly

Age of SNR when this happens depends on models for cooling functions, explosion energy and density.

roughly $t_{cool} \sim nkT/n^2 \Lambda(T)$ -~$4x10^4 yr T_6^{3/2}/n$

($\Lambda(T)$ is the cooling function)

phase starts when $t_{cool} < t_{Sedov}$ $T_6 < E^{1/7} n^{2/7}$

Between 17,000 and 25,000 years (assuming standard E_o and n_1)

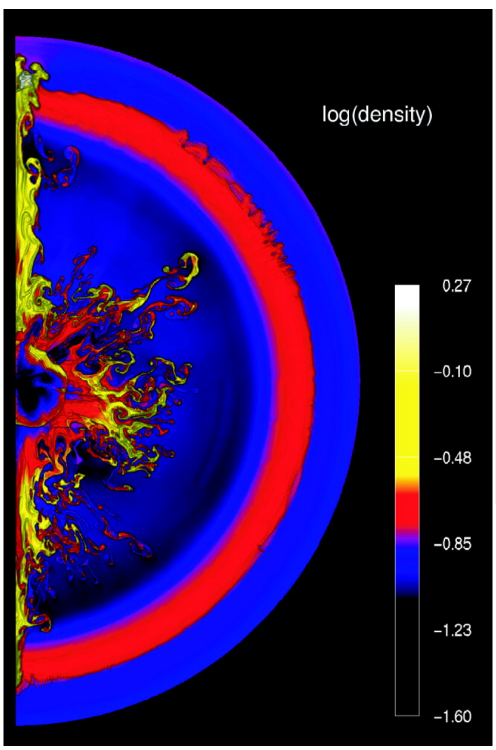
Then: THE END... SNR merges with surrounding medium

End of Snowplough Phase- Draine sec 39.1.4

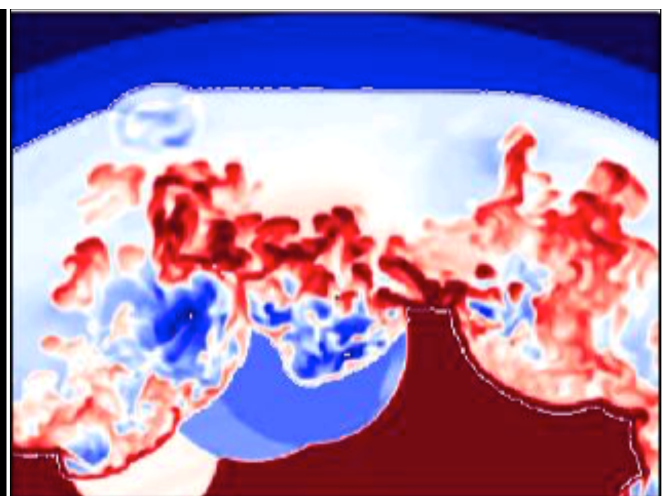
- The strong shock gradually slows (radiative losses and accumulation of 'snowplowed' material) – evolution dominated by momentum conservation, radiative cooling dominates, energy not conserved
- cooling timescale $tcool \sim nkT/n^2\Lambda(T) \sim 4x10^4 yrT_6^{3/2}/n$
- Shock compression declines until $v_{shock} \sim c_s$ (sound speed); no more shock
- Using this criteria the 'fade away' time
- $t_{fade} \sim ((R_{rad}/t_{rad})/c_s)^{7/5}\ t_{rad}$
- $t_{fade} \sim 1.9x10^6$ yrs $E_{51}^{0.32}\ n^{-0.37}(c_s/10km/sec)^{-7/5}$
  - $c_s = 0.3km/sec(T/10k)^{1/2}$
- $R_{fade} \sim 0.06kpc\ E_{51}^{0.32}\ n^{-0.37}(c_s/10km/sec)^{-2/5}$
- $v \sim 200km/sec(t/3x10^4 yr)^{-3/4}$

Complexities

- We have been using simple analytic models
- The situation, as usual is more complex due to instabilities and structure in the gas into which the shock runs.



Kifonidis et al. 2000

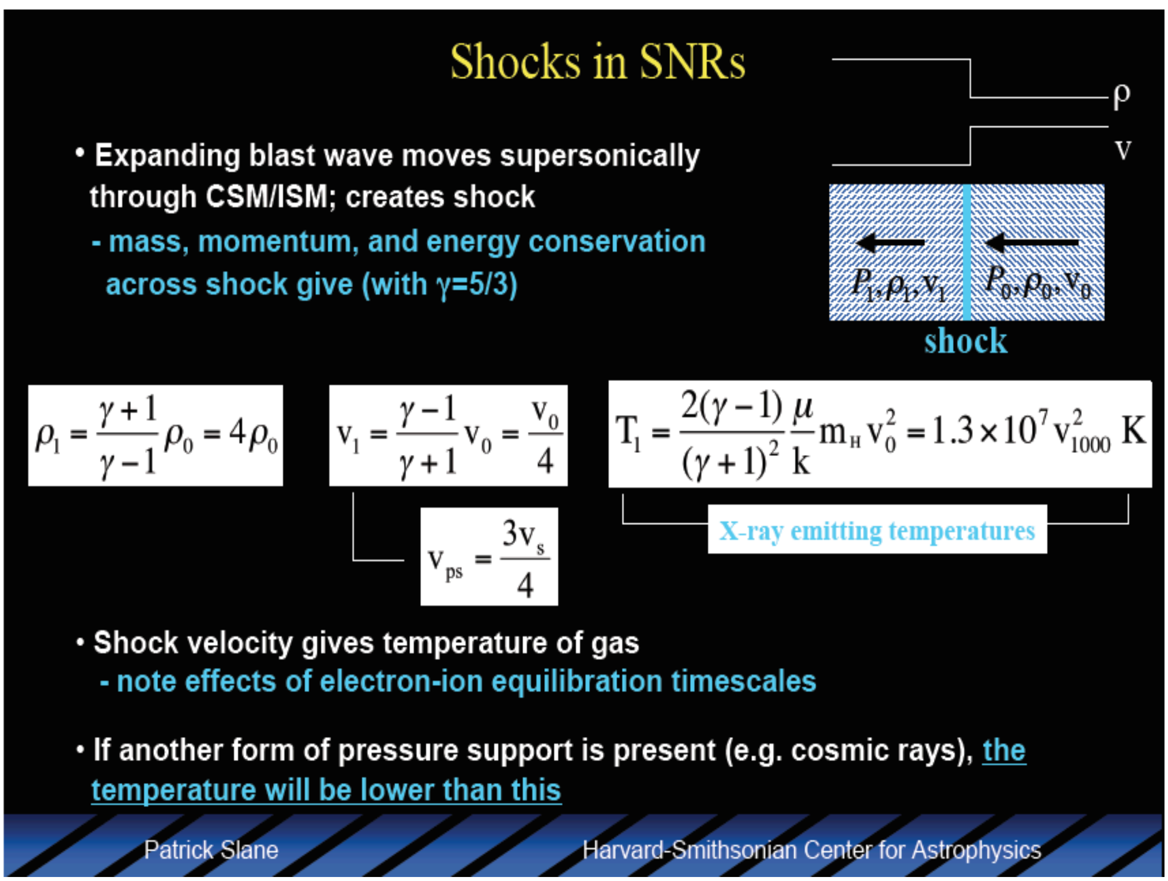


Fe bubbles Blondin et al. 2001

Instabilities

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

Summary of Lecture Next 5 Slides



- Kinetic energy of expansion (KE) is transfered into internal energy - total energy remains roughly the same (e.g. radiative losses are small)
- The temperature of the gas is related to the internal energy

$$T \sim 10^{6} k\ E_{51}^{1/2}\ n^{-2/5} (t/2x10^{4} yr)^{-6/5}$$

for typical explosion energies and life times the gas emits in the x-ray band

- measuring the size (r), velocity (v) and temperature T allows an estimate of the age

$$\tau_{Sedov} \sim 3x10^{4} T_{6}^{-5/6} E_{51}^{1/3} n^{-1/3} yr$$

- at T ~10^{6}-10^{7} k the x-ray spectrum is line dominated

- Free Expansion Phase

the ejecta expands freely into the interstellar medium. The expanding envelope compresses the ISM, creates a shock wave because of its high velocity, and sweeps up the ISM. During this initial phase, the mass of gas swept up is <<mass of the ejecta and the expansion of the envelope is not affected by the outer interstellar gas andit keeps its initial speed and energy.

- Adiabatic Expansion Phase

When mass of gas swept up > mass of ejecta the kinetic energy of the original exploded envelope is transferred to the swept up gas, and the swept up gas is heated up by the shock wave roughly independent of the physics of the explosion. The radiative losses from the swept up gas are low (energy is conserved) - adiabatic expansion phase.

The evolution during this phase is determined only by the energy of explosion E_0, the density of interstellar gas, and the elapsed time from the explosion t. A self similar solution relating the density, pressure, and temperature of the gas, and the distribution of the expansion velocity exists (Sedov-Taylor)

Sedov-Taylor Solution

- nice discussion in Draine sec 39.1.2
- assume a spherical shock of radius R and it has a a power law dependence on energy of the explosion, E, time since explosion,t, and density of the medium into which it is running ρ.
- $R=AE^{\alpha}\rho^{\beta}t^{\eta}$
- with dimensional analysis (e.g. the powers to which mass length and time appear to get
- mass $\alpha+\beta=0$, length $1-2\alpha-3\beta=0$, $-2\alpha+\eta=0$ time

one solves this to get
$\alpha=1/5$, $\beta=-1/5$, $\eta=2/5$

or $R=AE^{1/5}\rho^{-1/5}\,t^{2/5}$

putting in the physics and numbers

$R=1.54\text{x}10^{19}\text{cm}\ E_{51}{}^{1/5}n^{-1/5}\ t_3{}^{2/5}$

(we have switched units, n is particle density, t_3 is in units of 10^3 years, E_{51} is in
units of 10^{51} ergs.

$v_s=1950\text{km/s}\ E_{51}{}^{1/5}n^{-1/5}\ t_3{}^{-3/5}$

$T=5.25\text{x}10^7\text{k}\ E_5{}^{2/5}n^{-2/5}\ t_3{}^{-6/5}$