Supernovae

- Supernova basics
- Supernova types
- Light Curves
- SN Spectra – after explosion
- Supernova Remnants (SNRs)
- Collisional Ionization

Supernova Basics

- Supernova (SN) explosions in our Galaxy and others reach a peak luminosity of $\sim 10^{10} L_{\odot}$.
- Initial expansion velocities on the order of ~20,000 km/sec
- Due to collapse of white dwarf in a binary system (type Ia) or collapse of a massive star (type II, Ib, Ic), when electron degeneracy pressure can't hold off overlying layers
- Produce shock fronts which compress and collisionally ionize the ISM (shock front slows down over time)
- Enrich the ISM with heavy elements, including those that cannot be produced other ways (elements heavier then Fe)
- Typical SN rates ~ 1/Galaxy/century
- "Recent" local supernovae: 1006 AD, 1054 AD (produced Crab nebula), Tycho's (1572), Kepler's (1604) , SN 1987A (in the LMC)

Supernova Types

- Type based primarily on appearance of spectra near peak luminosity.
- Type I – no Hydrogen lines
- Type II – Hydrogen lines present
- Subtypes (spectra obtained ~1 week after peak luminosity):

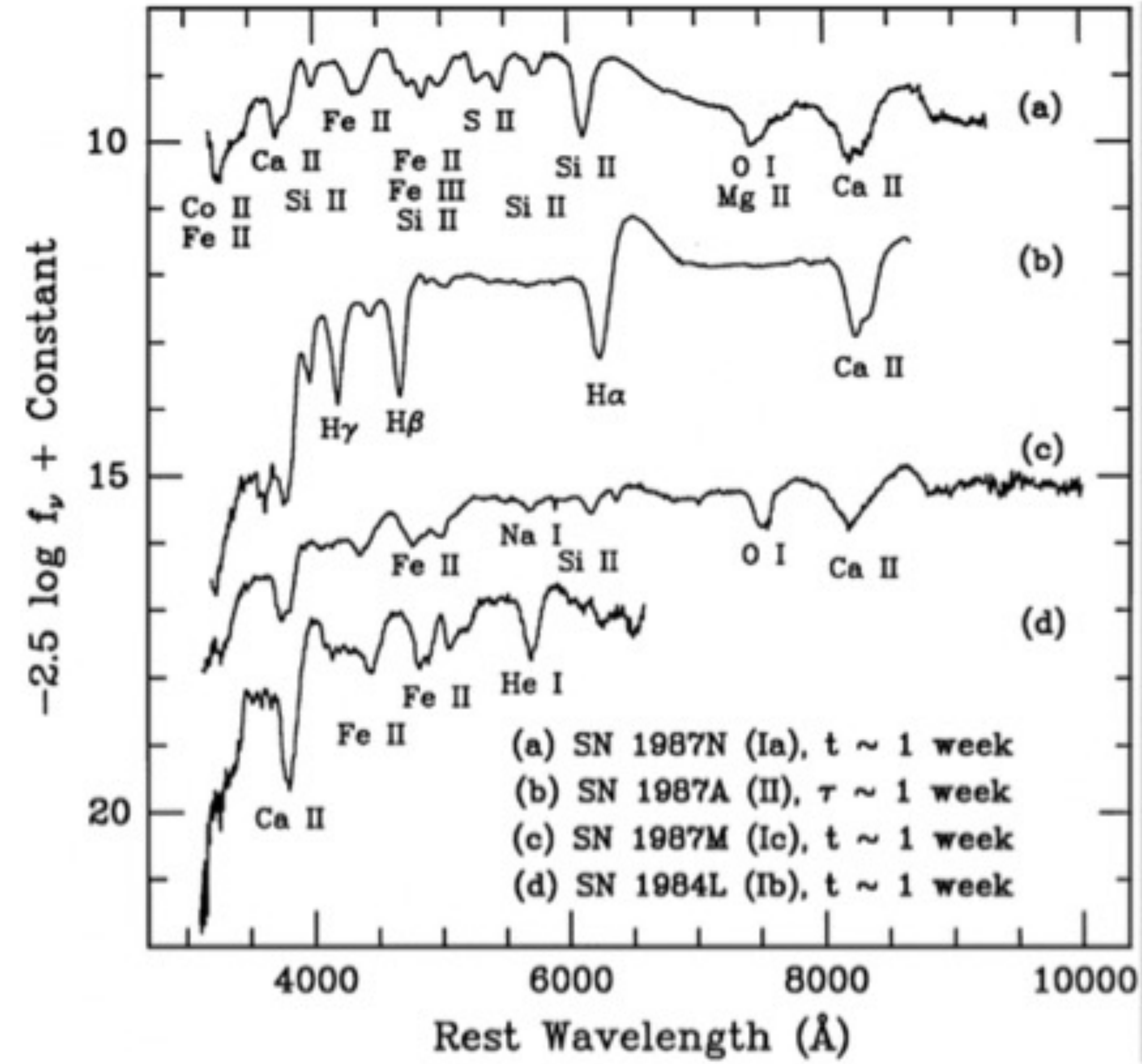
Ia – strong Si II absorption

Ib – strong He I absorption

Ic – no He I and absent or weak Si II absorption

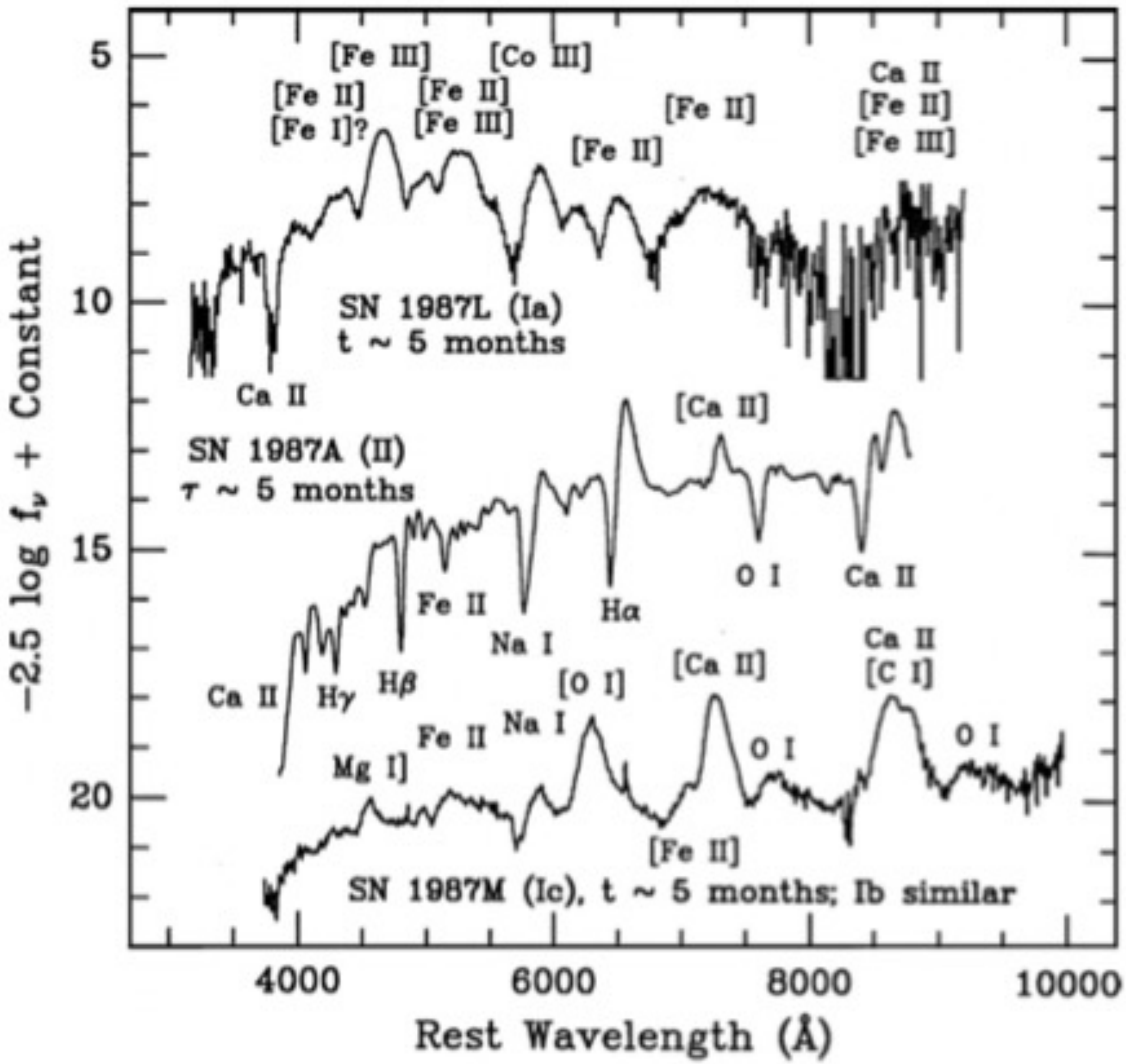
II – Hydrogen (Balmer) lines in absorption and/or emission

Supernovae Spectra – Early Stages



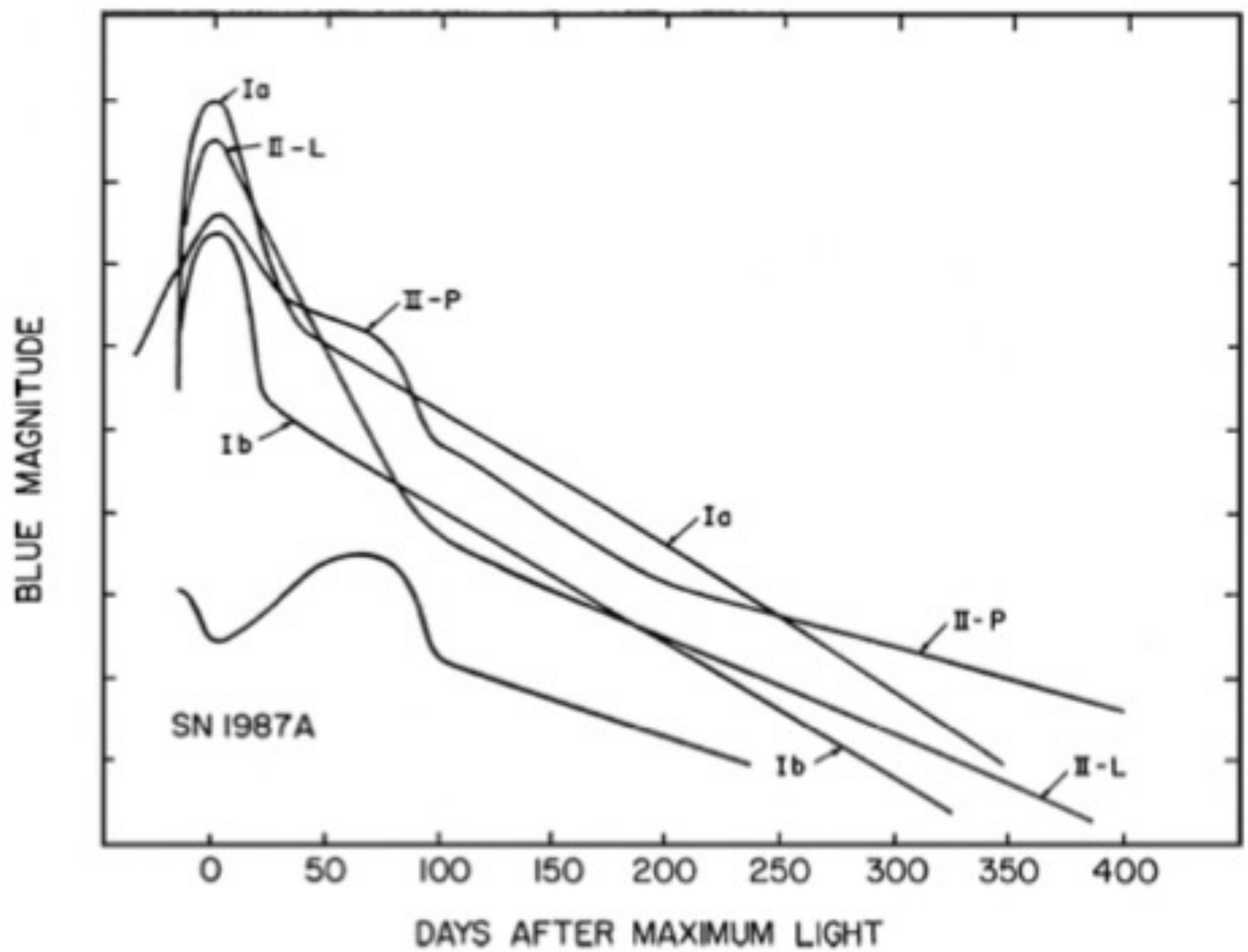
(Filippenko, A.V. 1997, ARAA, 35, 309)

Supernovae Spectra – Later Stages



(Filippenko 1997)

Supernova Light Curves

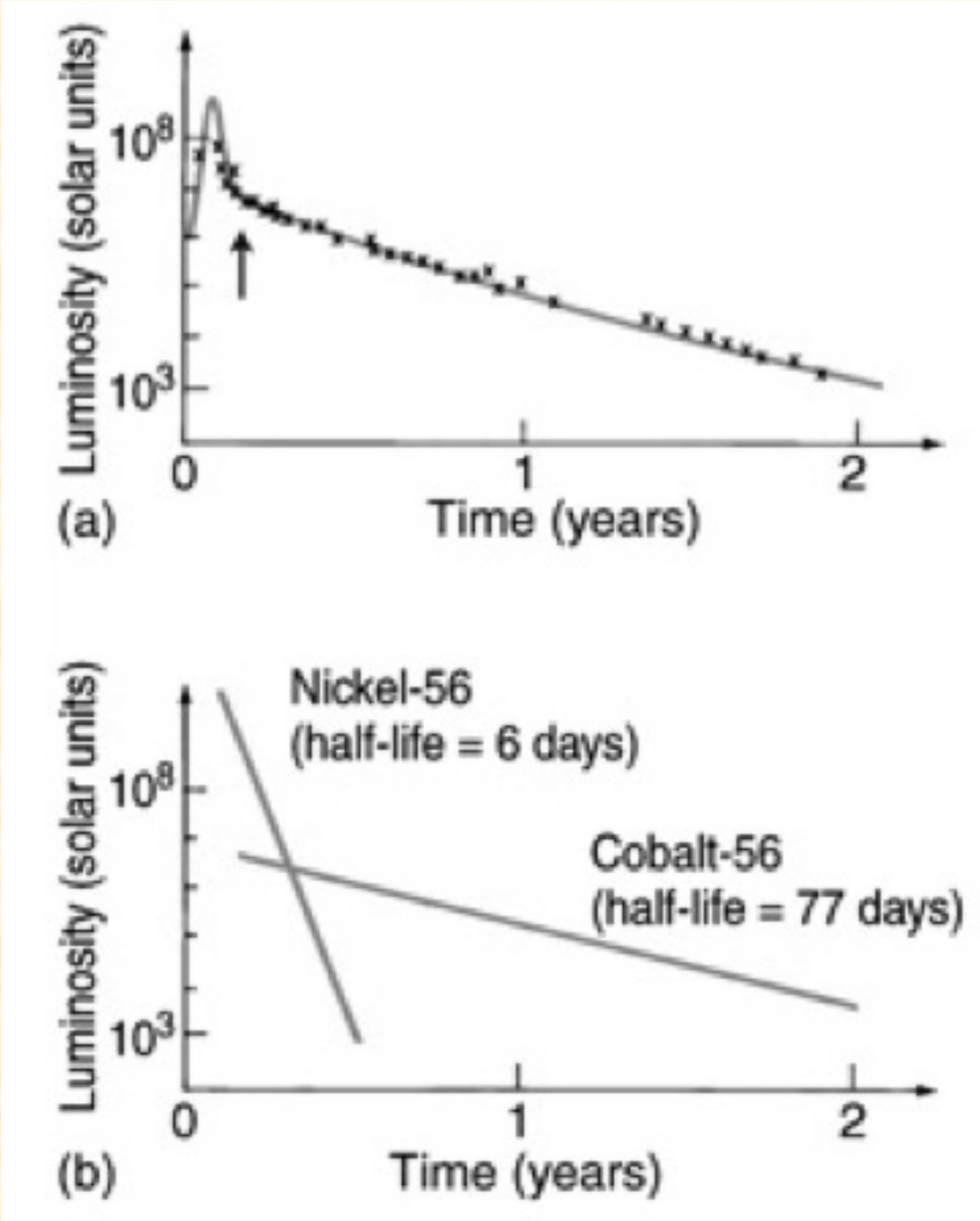


(Filippenko 1997)

I - homogeneous, peak followed by smooth decline

II - much dispersion, II-L: smooth decline, II-P: plateau

SN Ia Light Curve



^{56}Ni decays to ^{56}Co, which decays to ^{56}Fe

Supernova Types - Interpretation

- Type Ia: binary white dwarf plus red giant or supergiant
  - white dwarf near Chandra limit: Mass = $1.4M_{Sun}$
  - mass transfer from companion instigates WD collapse (can no longer support itself with electron degeneracy)
  - collapse leads to carbon deflagration (subsonic) runaway
  - WD is completely destroyed
- Type II: Collapse of high mass star (initial mass > 8 $M_{\odot}$ on Main Sequence) due to exhaustion of nuclear fuel
  - neutron star (pulsar) or black hole remnant
  - rebound provides supernova explosion, neutrinos provide most of the force
- Type Ib: collapse of massive star, no H
- Type Ic: collapse of massive star, no H or He

(Ib and Ic likely from Wolf-Rayet stars that have lost their outer envelopes due to stellar winds or other mass loss.)

Spectral Evolution

- Early spectra (~ 1 week after peak) show continuum emission from expansion of optically thick gas ("photosphere")
  - absorption or P-Cygni lines from outer layers
  - widths of lines indicate velocities of ~20,000 km/sec
  - UV flux depressed due to "line blanketing"
- Later spectra (~ weeks to months) show strong low-ionization lines as gas cools off
  - Type Ia show strong [Fe II], [Fe III] lines
  - Type Ib, Ic show lines of intermediate mass elements (O, Ca)
  - Type II are similar to Ib and Ic, but show Balmer lines
- Eventually (years), collisions ionize the ISM, producing a supernova remnant, with typical nebular lines (O III], etc.)
- For young type II supernovae, a pulsar (e.g., the Crab Nebula pulsar) can ionize the gas by synchrotron radiation

Supernova Remnants - Evolution

- Extreme supersonic motion produces a shock wave
- Initial expansion is adiabatic.
- ISM gas passing through shock front is compressed and collisionally ionized.
- The shocked gas cools by radiation. Expansion is characterized by two different temperatures, pressures, and densities on either side of the shock.
- Ionization balance given by:

$$n(X^i)\, n_e q_{ion}(X^i,T) = n(X^{i+1})\, n_e \alpha(X^i,T)$$

$$\text{where } q_{ion}(X^i,T) = \int_{\chi=1/2mv^2}^{\infty} v\, \alpha_{ion}(X^i,v)\, f(v)\, dv$$

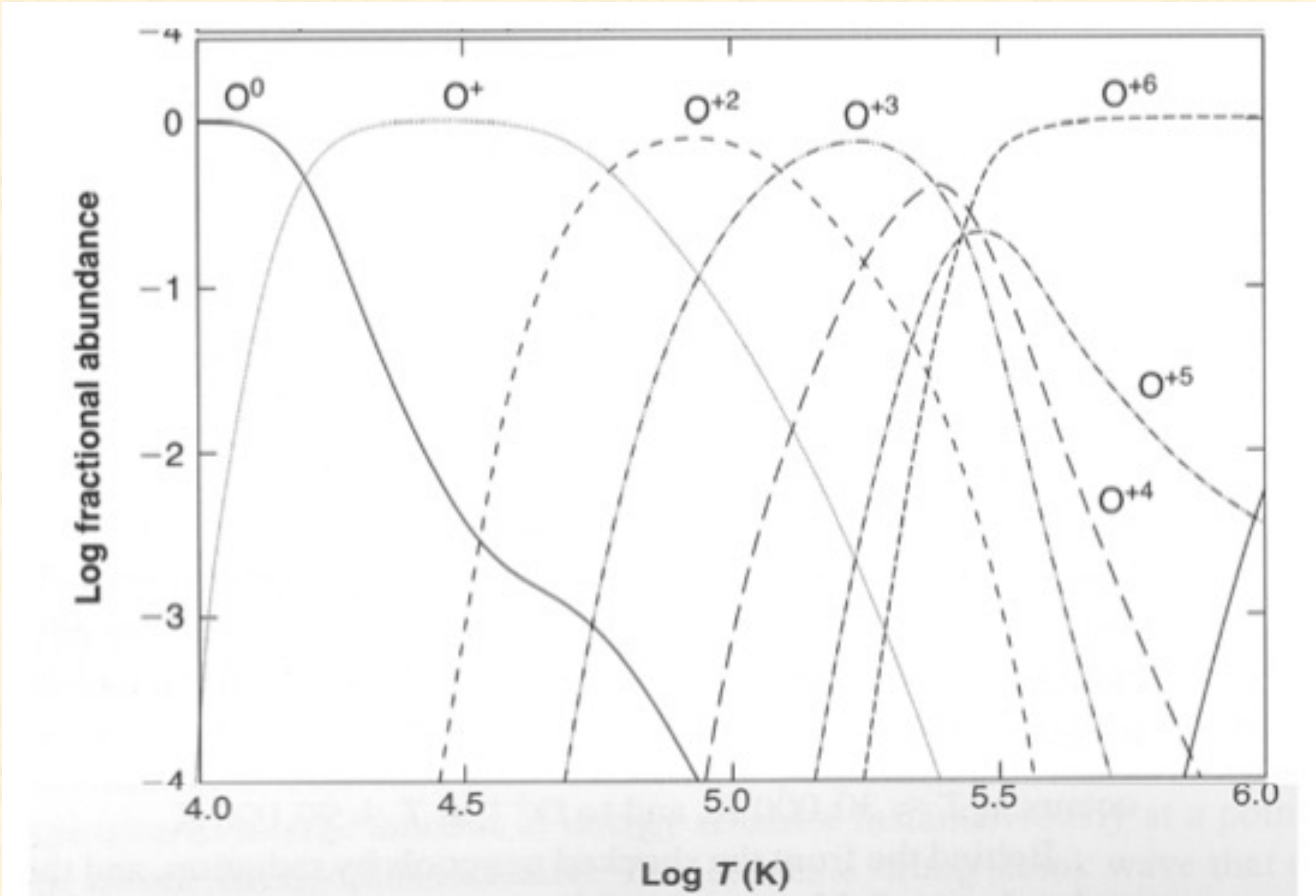
where χ = ionization potential

Additional model considerations:

- recombination in shocked gas produces ionizing photons, which "pre-ionize" unshocked gas
- charge exchange is significant

- In high-density clumps, temperatures reach >30,000K (higher than photoionized nebulae)
  - confirmed by high [O III] $\lambda 4363/\lambda 5007$ ratio
- X-rays penetrate deep into high-column clouds, to partially ionized gas
- In low density regions, shocked gas can reach temperatures of 10^6 K, which *produces* X-rays
- Mass swept up by shock wave: $10^2 - 10^3\ M_{\odot}$!

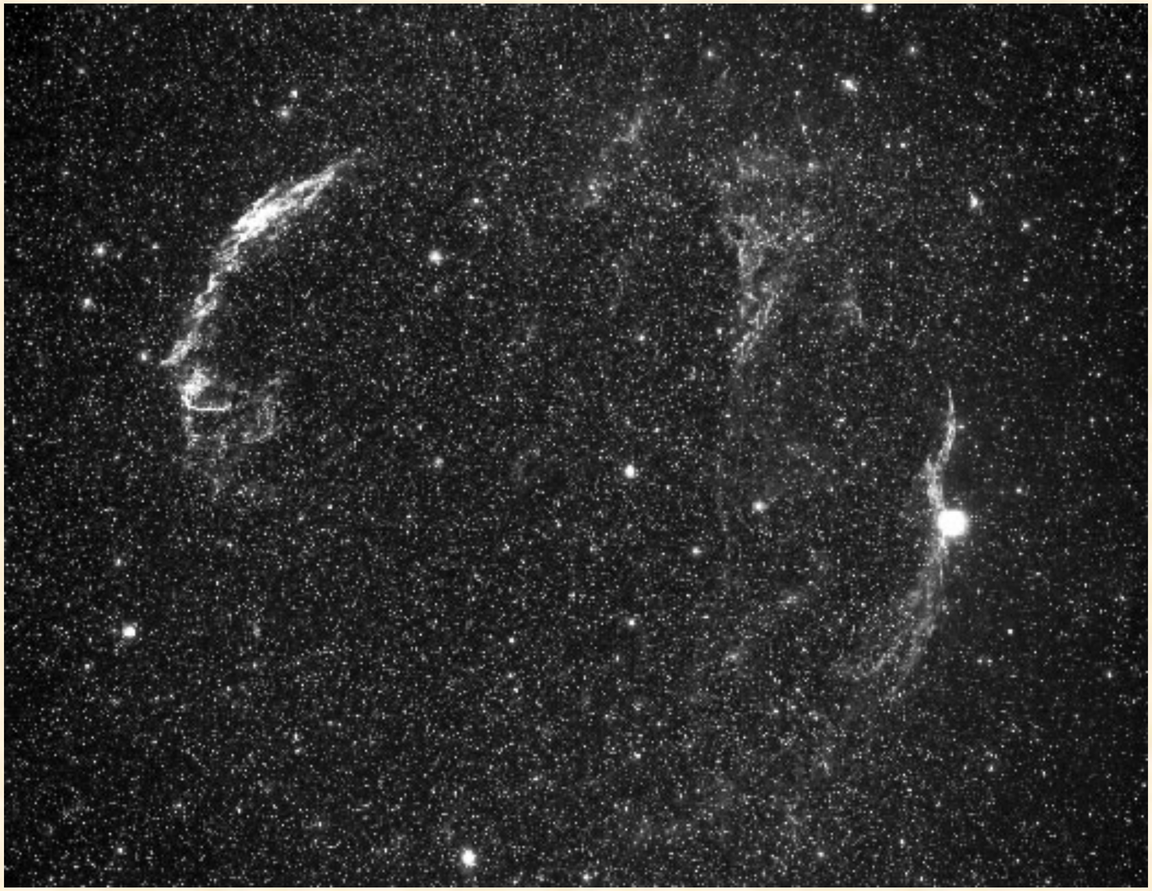
Collisionally Ionized Gas



(Osterbrock, p. 300)

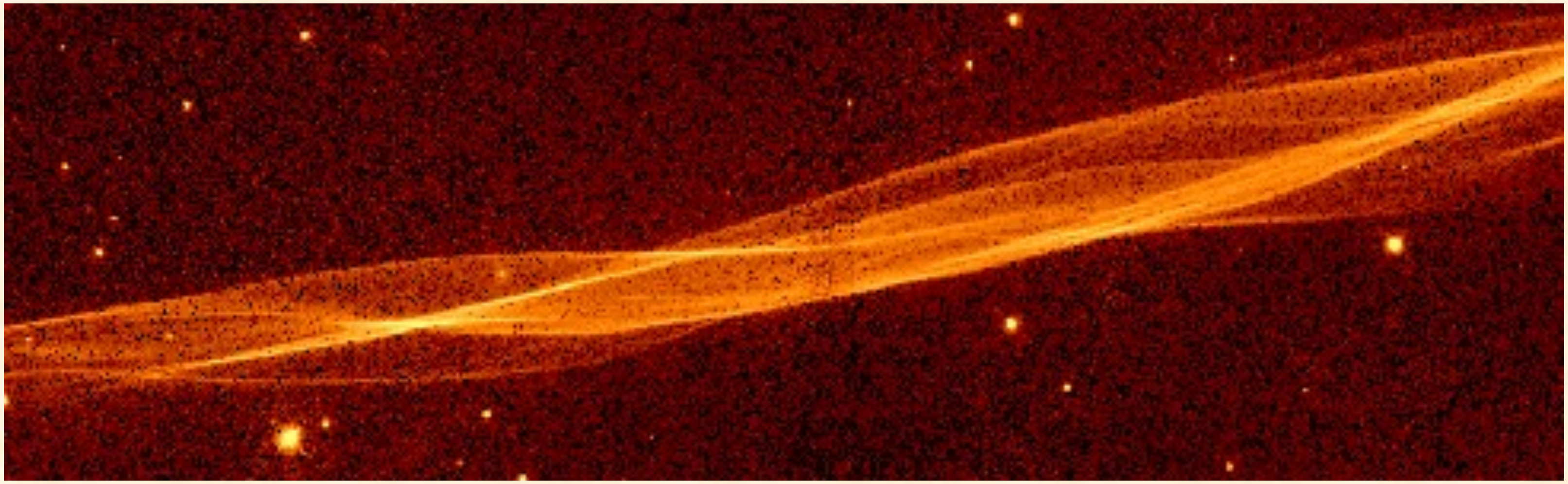
- require high gas temperatures to get highly ionized species

Ex) Cygnus Loop



- Older Supernova Remnant (SNR): 25,000 years
- 3° in diameter on sky, many filaments
- No central remnant (i.e., pulsar) has been found

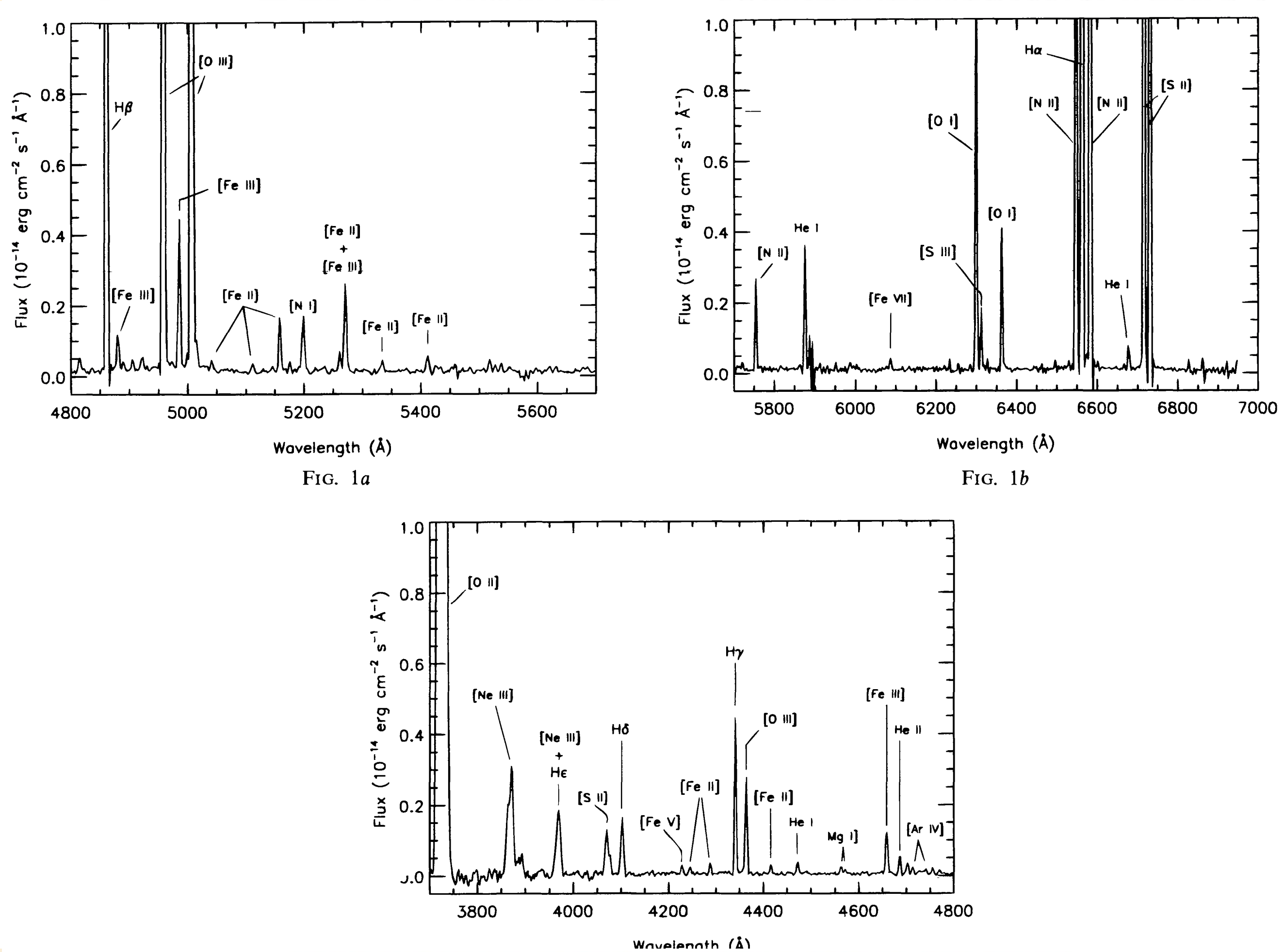
Cygnus Loop



(HST, narrow-band Hα)

- High and low-ionization filaments
- Expansion velocity ~ 100 km/sec
- Distance ~ 800 pc
- Collisionally ionized gas

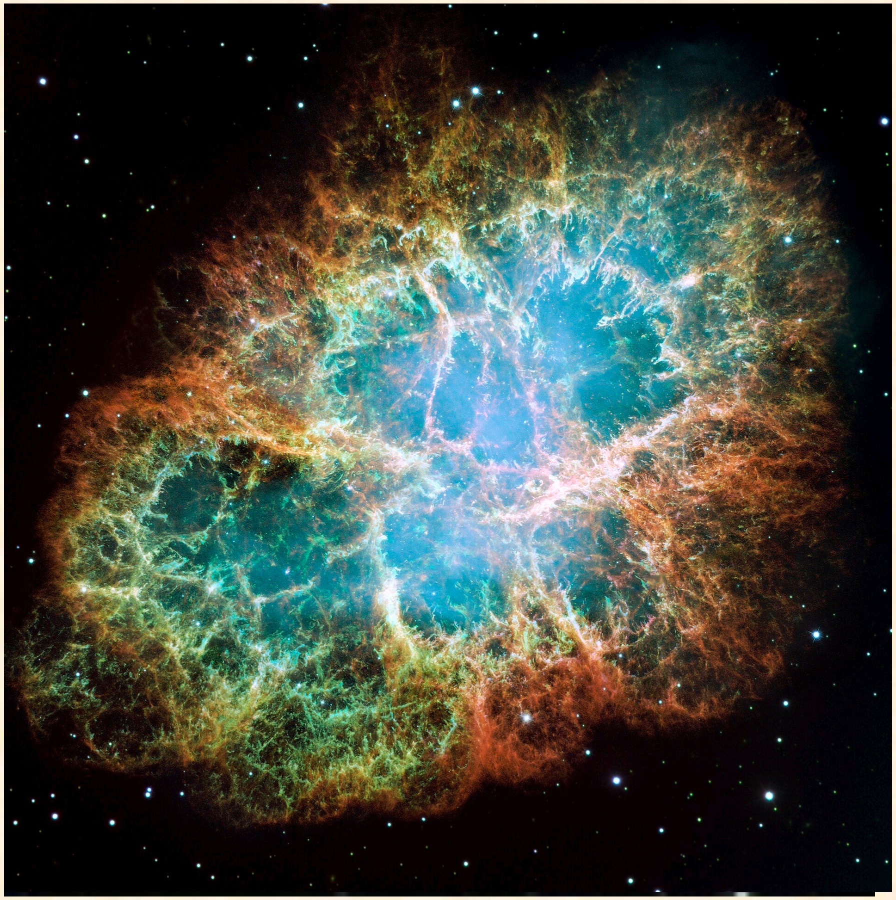
Spectrum of Cygnus Loop Filament



(Fesen & Herferd, 1996, ApJS, 106, 563)

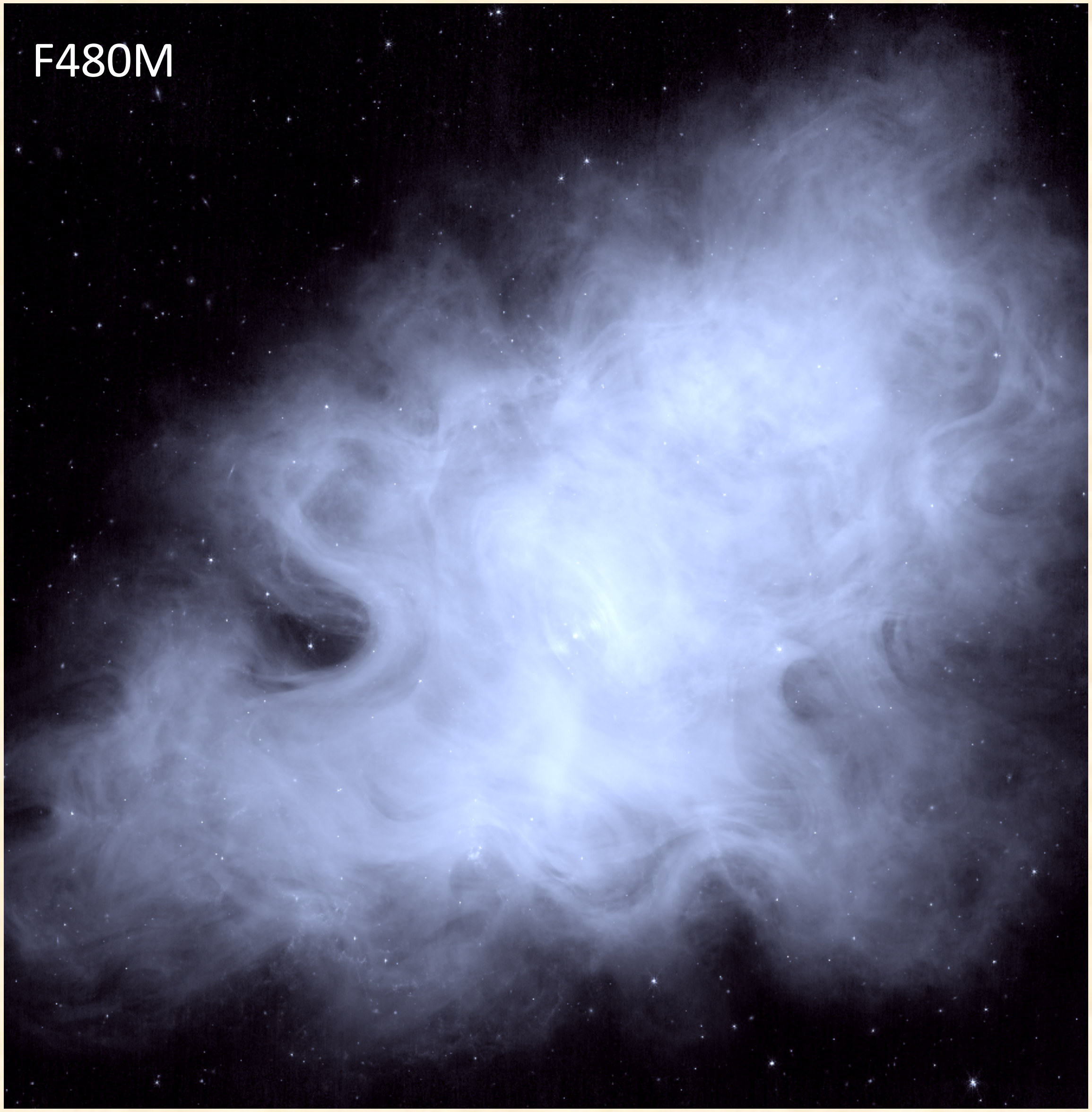
- strong lines from a wide range in ionization
- strong [O III] λ4363 indicates high temperature (30,000 K)

Crab Nebula - HST

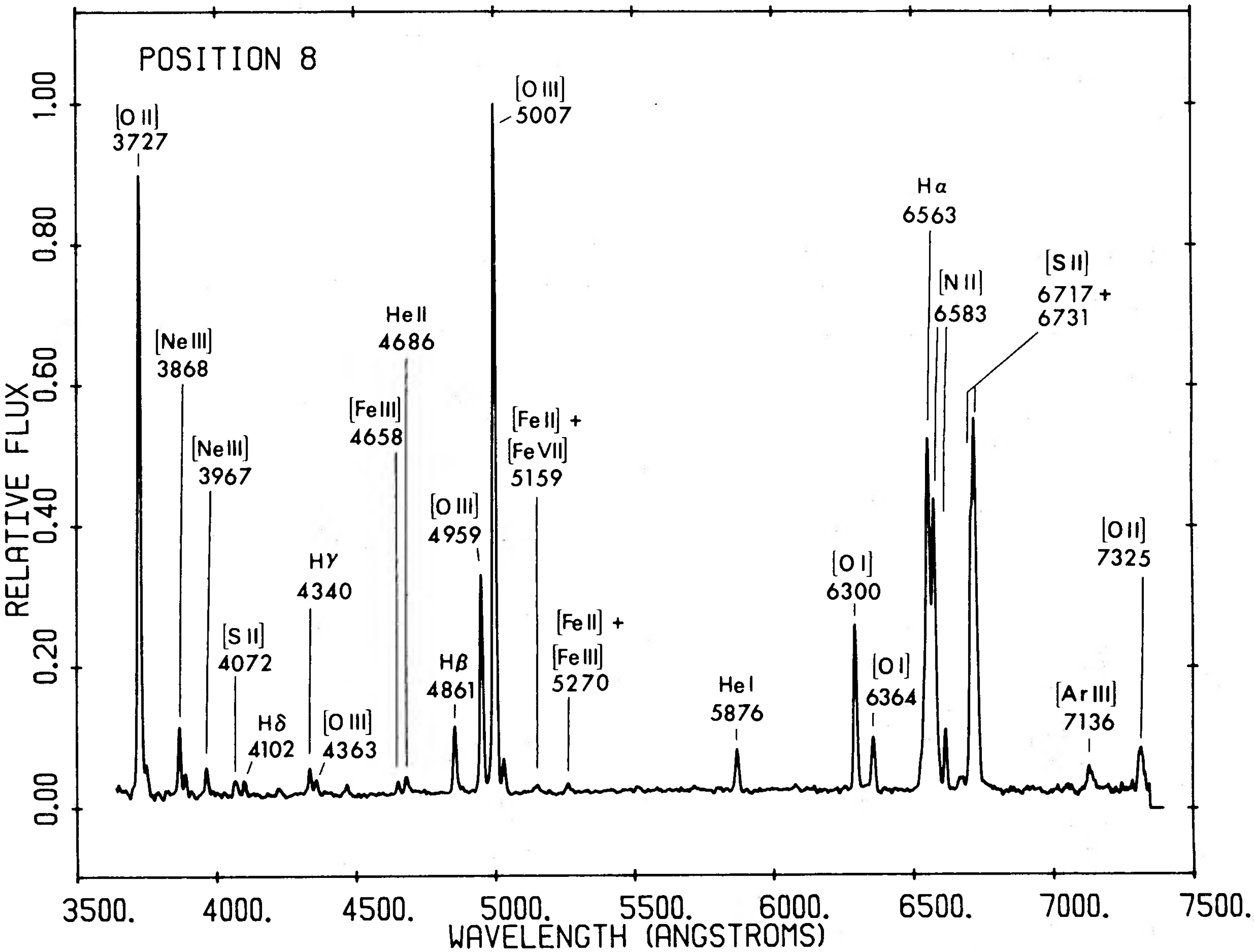


- Young SNR (remnant of SN in 1054 AD)
- Gas concentrated in filaments, high resolution shows knots like "beads on a string"
- Expansion velocity is ~1500 km/sec, proper motion of filaments gives distance of ~1800 pc

Crab Nebula – JWST (Synchrotron Radiation)



Spectrum of Crab Filament



(Fesen & Kirshner, 1982, ApJ, 258, 1)

- similar to AGN spectra, lines are narrower, [S II] and [O II] stronger

- Line ratios consistent with photoionization by "hard" continuum (X-rays in addition to EUV):

$$F_\nu \propto \nu^{-\alpha} \quad \text{where } \alpha \approx 0.5 \text{ at high } \nu$$

- Nebular spectrum: high and low-ionization filaments
  - mostly a density effect; remember the ionization parameter:

$$U = \frac{\int_{\nu_0}^{\infty} \frac{L_\nu}{h\nu} d\nu}{4\pi r^2 c n_e} \quad \text{lower density} \rightarrow \text{higher } U$$

- Luminosity of neutron star (pulsar) not enough to ionize gas
- Ionizing radiation is due to synchrotron (electrons spiraling in strong magnetic field) – produces the amorphous blue region
- X-rays create a partially ionized zone, deep in high column-density clouds – responsible for strong [O I], [S II] lines

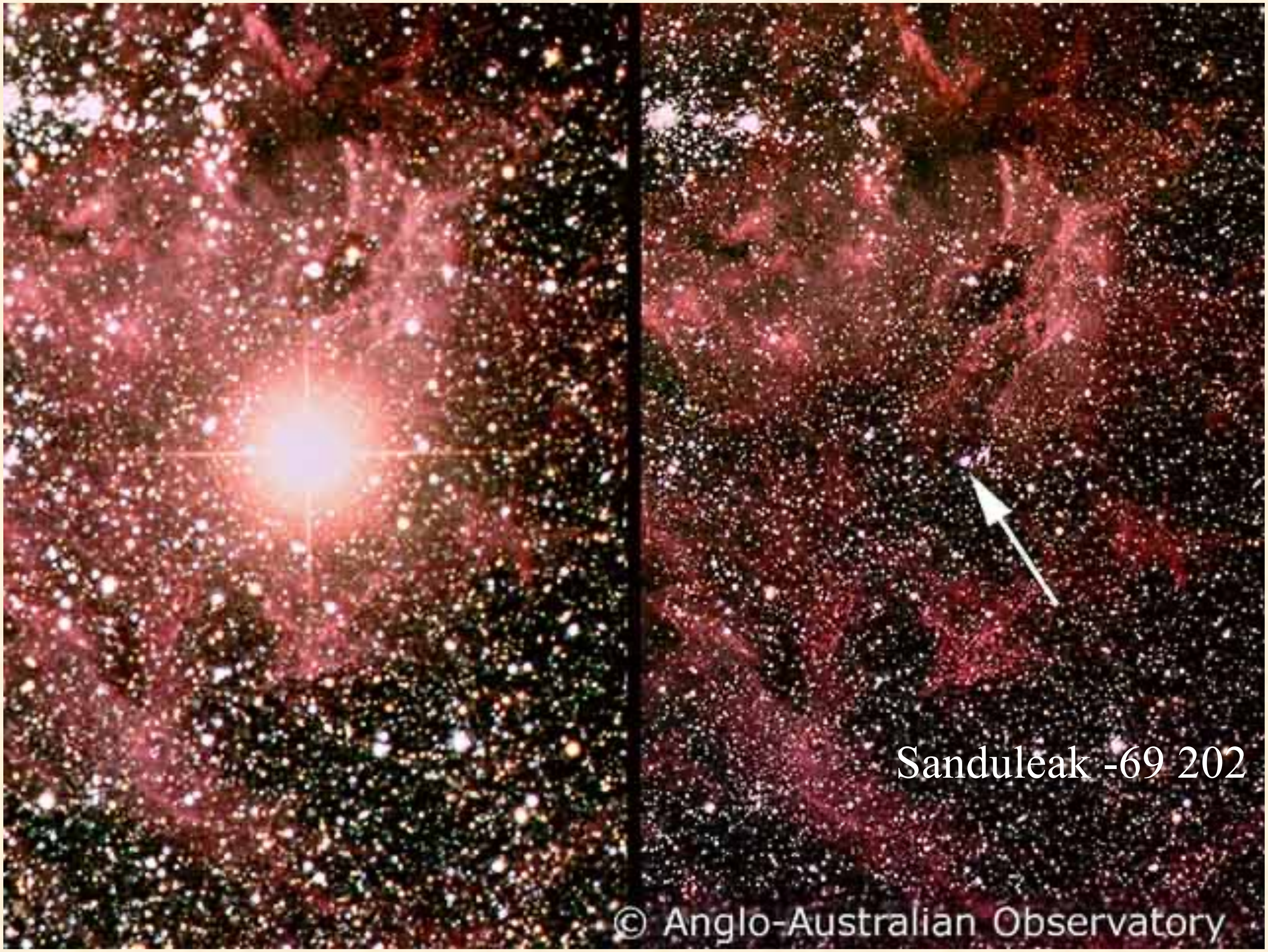
Shock vs. Photoionized Gas

Observed emission-line relative intensities in shock-heated and photoionized environments

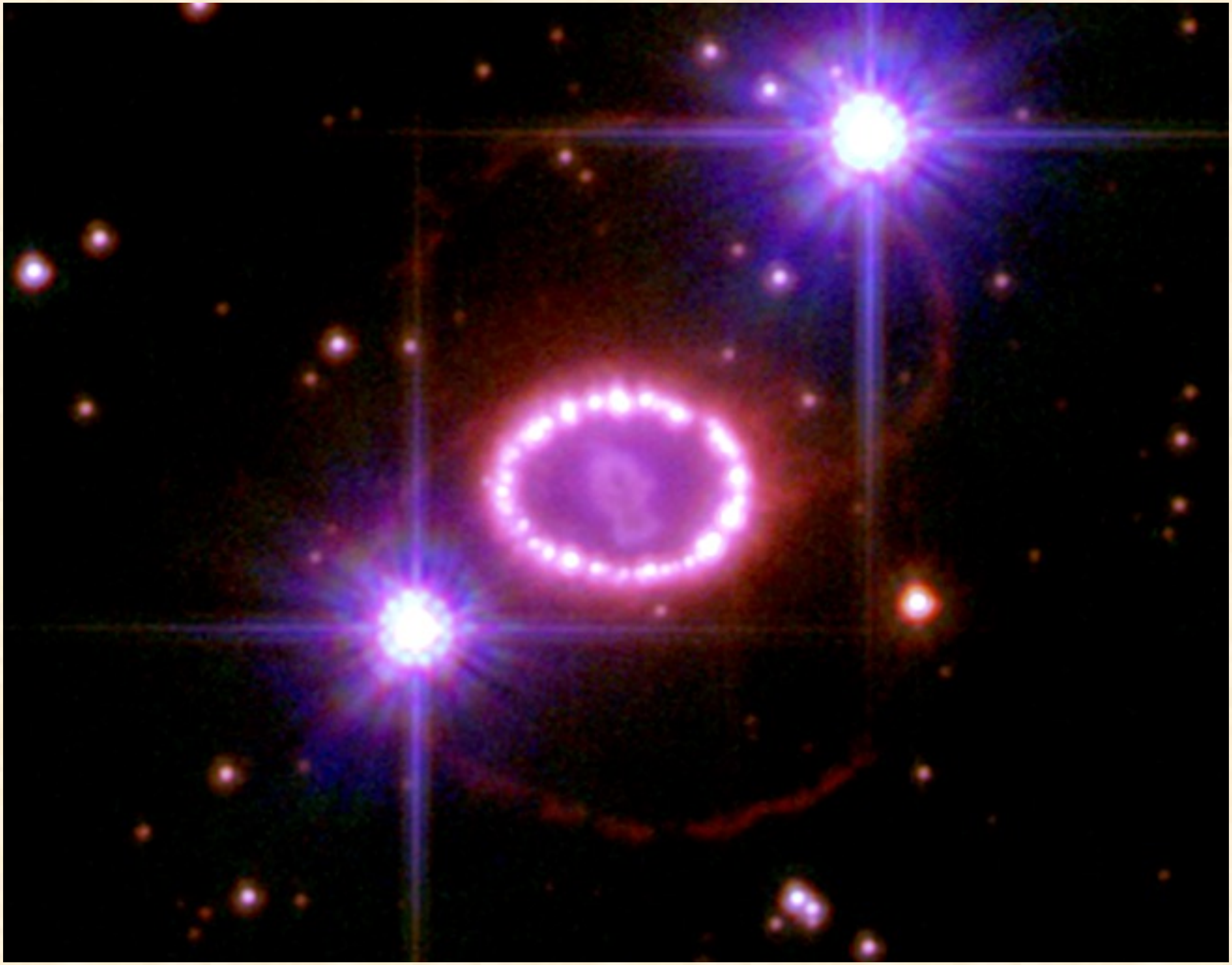
Ion	Wavelength (Å)	Orion	Cas A
C IV	1550	<0.1	0.76
C III]	1909	0.18:	6.46
[O II]	3727	1.47	1.28
[O III]	4363	0.0139	0.22
Hβ	4861	1.00	1.00
[O III]	4959	1.00	1.12
[O III]	5007	3.02	3.38
[O I]	5577	0.00058	0.07
He I	5876	0.134	0.07
[O I]	6300	0.0012	0.31
[N II]	6548	0.94	1.00
Hα	6563	2.81	3.00
[N II]	6583	0.596	2.98
[S II]	6717	0.0314	1.15

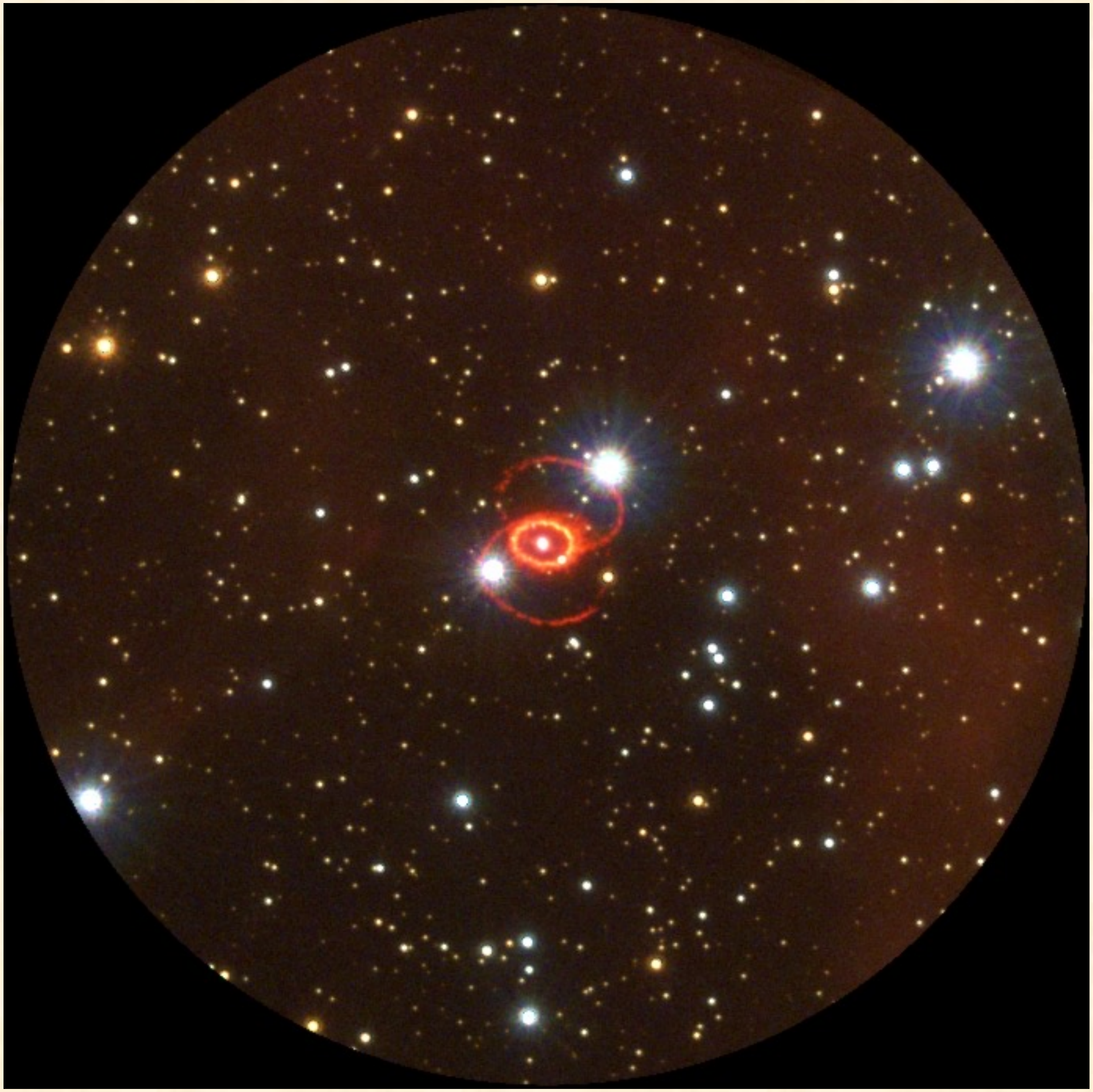
(Osterbrock, p. 310)

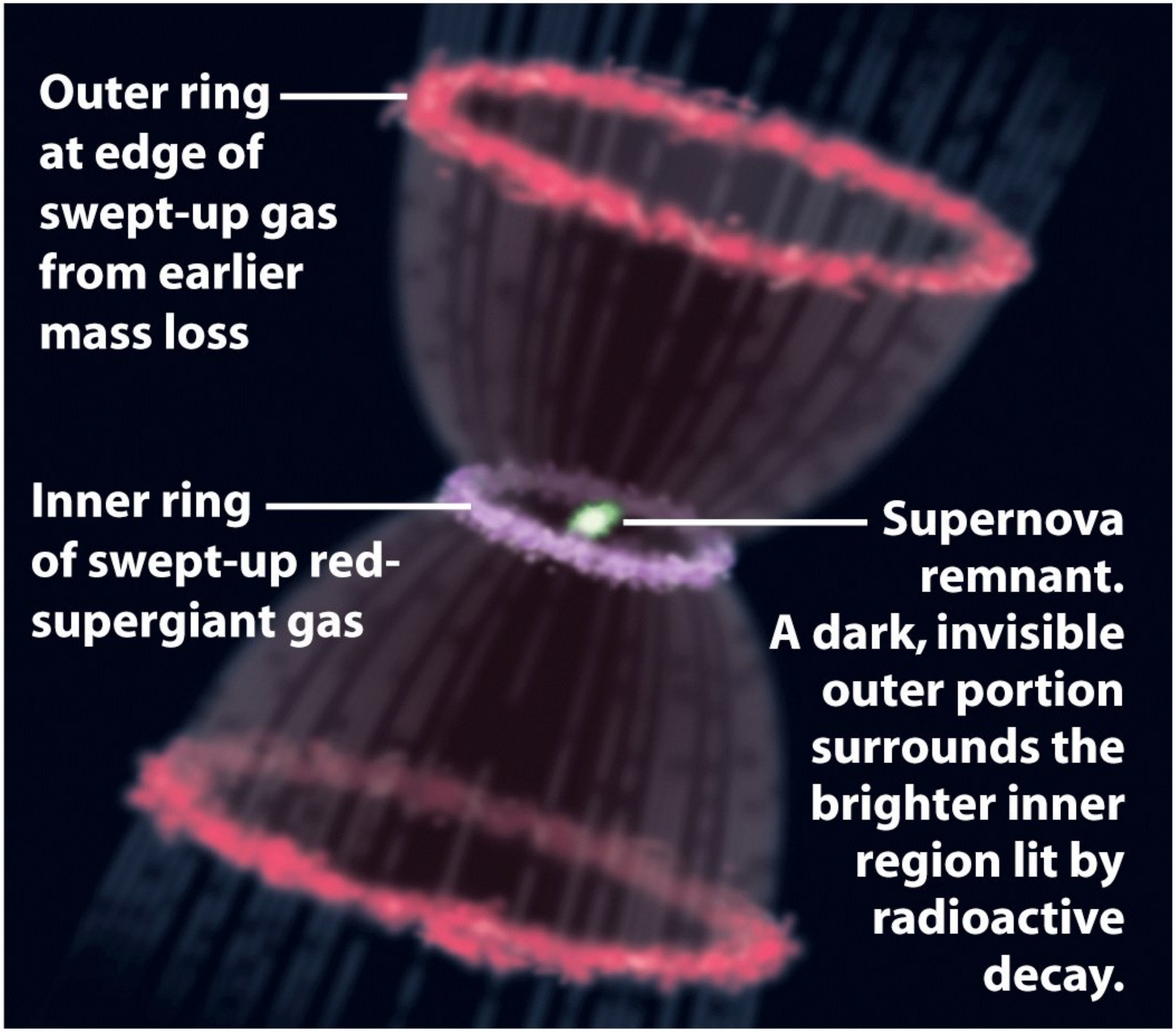
Supernova 1987A



Explosion of blue supergiant in the LMC

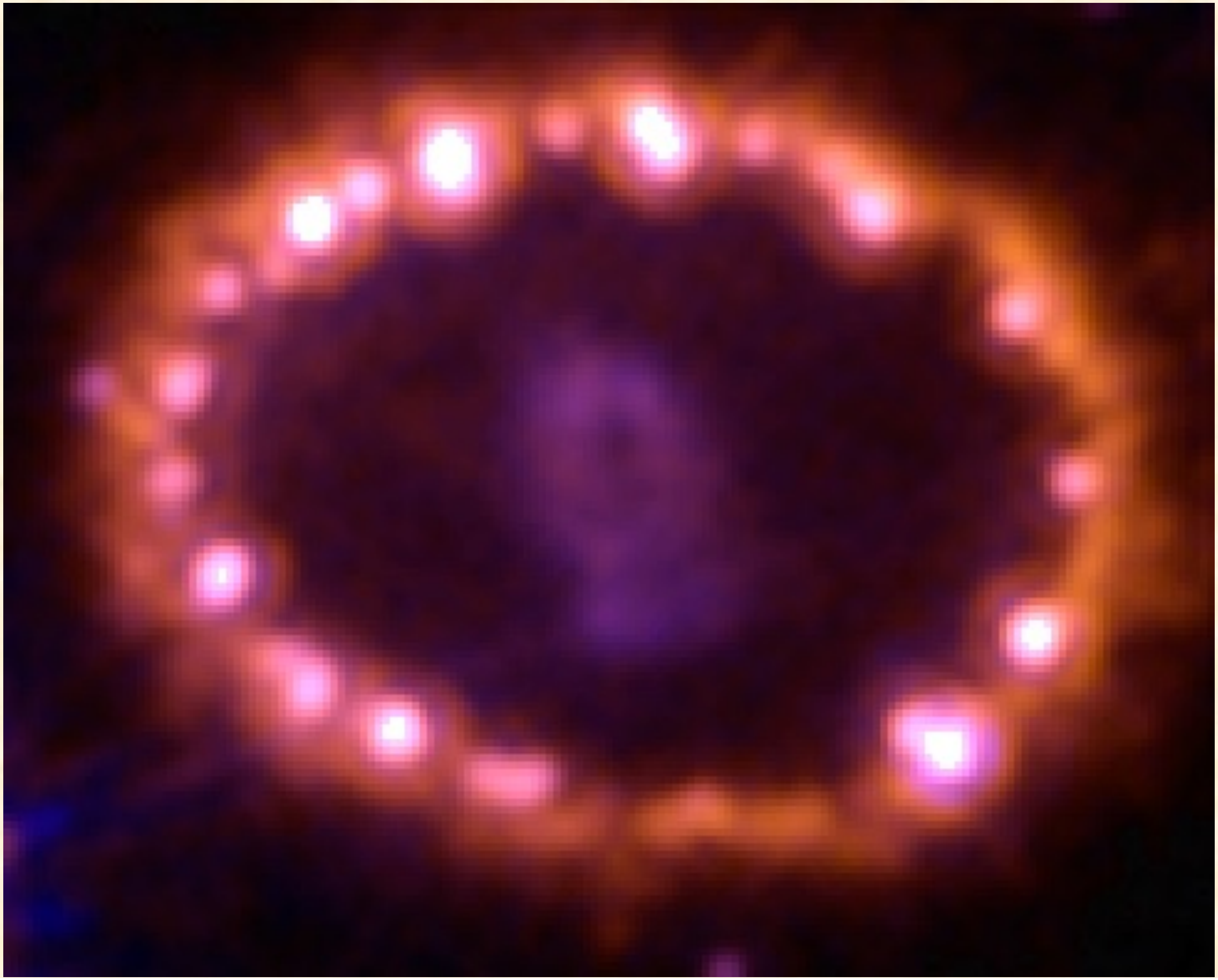






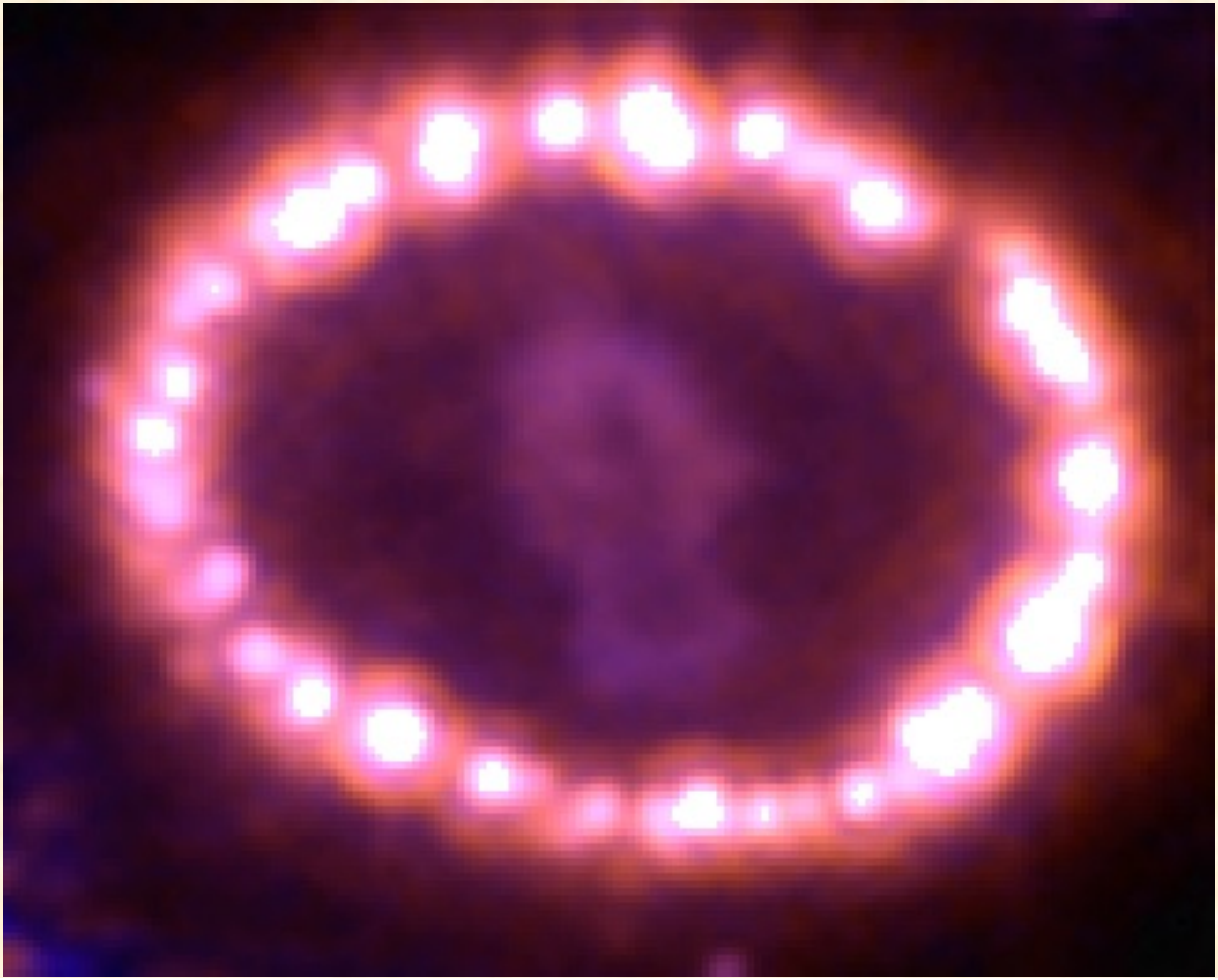
An explanation of the rings

2003

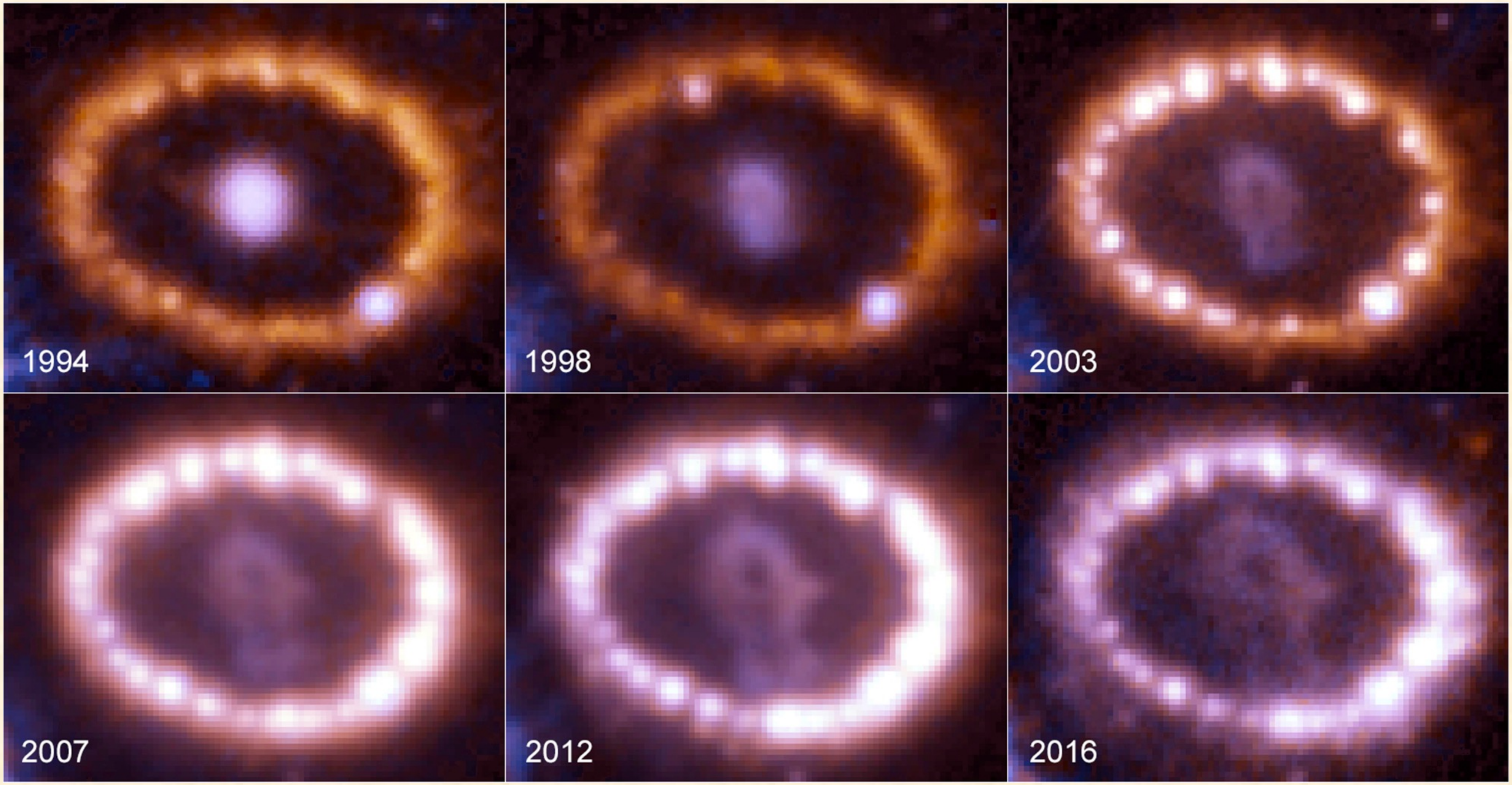


Impact of shock front

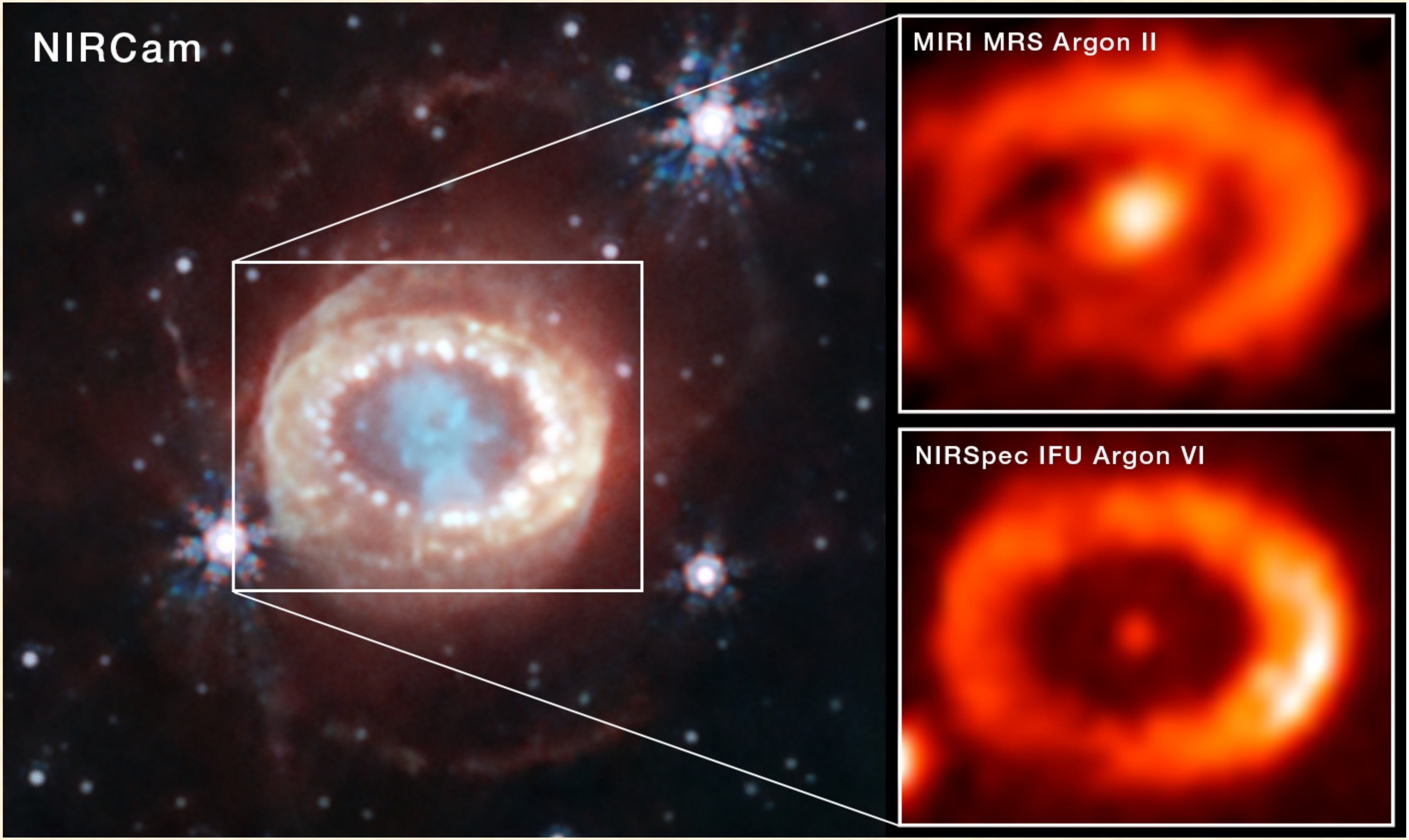
2006



Shocked gas fading



Supernova 1987A – JWST



Credit: NASA, ESA, CSA, and M. Matsuura

- High-ionization core: Possible evidence for neutron star