

AGNAGN semi

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Section 12.4 – 12.5

12.4 The Cygnus loop

Feature of the Cygnus loop

- large (3° in diameter) emission nebula
- filamentary structure.
- expand with a proper motion: $0.03'' \text{ yr}^{-1}$
- inside: hollow (no optical observable gas)
- No central star
- Approximate age from velocity and size: 5,000 year



Figure 12.3

NGC 6960–6992–6995 (Cygnus Loop). Taken with the Palomar 48-inch Schmidt telescope in red light, chiefly $H\alpha$, $[N II]$, and $[S II]$. (Palomar Observatory photograph)

The Cygnus loop

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Optical line spectra of the filament of the Cygnus loop

- great variations in the spectrum from one filament to another
- [O II] 3727 is relatively strong with respect to [O III] 4959, 5007
- [O I] 6300, 6364 and [S II] 6717,6731 are stronger in both of them than in typical planetary nebulae.
- line intensities have been corrected for interstellar extinction $E(B - V) = 0.10$
 - value derived from theoretical and observed H I recombination line ratios

Striking feature

- **strong [O III]4363 line**
- electron densities (from [O II] A3729/A3726 and [S II] A6716/A6731): low ($n_e < 300 \text{ cm}^{-3}$)
- temperature in the O^{++} zone is relatively high.
 - temperatures from [O III] (A4959 + A5007)/A4363:
 - $T = 29,000 \text{ K}$ in the high-ionization filaments
 - $T = 31,000 \text{ K}$ in the low-ionization filaments
- **Too high temperature cannot be explained by photoionization.**
- Possible way: **shock-wave heating**
 - conversion of kinetic energy to heat
 - energy of the Cygnus loop is high -> Cygnus loop is remnant of a supernova

Table 12.6

Observed and predicted relative line intensities in Cygnus Loop

Ion	Wavelength (Å)	High-ionization filament		Low-ionization filament	
		Observed	Model	Observed	Model
N V	1240	261	418	<19	1
C II	1335	68	486	16	341
O IV]	1400	537	675	55	36
N IV]	1486	131	222	22	16
C IV	1550	575	6800	76	399
He II	1640	255	275	50	21
O III]	1664	712	537	150	142
N III]	1750	323	206	85	60
Si III]	1890	98	185	38	214
C III]	1909	1340	1420	646	617
C II]	2325	291	454	386	272
[Ne IV]	2420	66	219	—	9
[O II]	2470	69	43	68	27
[O II]	3727	1601	1730	1280	893
[Ne III]	3869	203	100	72	34
[S II]	4071	21	19	28	11
[O III]	4363	92	91	22	25
[Fe III]	4658	—	19	4	12
H β	4861	100	100	100	100
[O III]	4959	421	433	125	109
[O III]	5007	1388	1290	338	326
[N I]	5199	—	9	4	12
[N II]	5755	—	10	7	4
He I	5876	—	9	7	17
[O I]	6300	35	34	31	25
[O I]	6363	17	11	9	8
[N II]	6548	114	137	94	57
H α	6563	300	303	300	304
[N II]	6583	311	410	298	171
[S II]	6717	126	104	115	72
[S II]	6731	85	77	78	53
[Ar III]	7136	44	61	17	20
[O II]	7319	44	32	29	20
[O II]	7330	18	26	15	16

12.4 The Cygnus loop

Evolution of supernova remnant

1. homogeneous and low-density interstellar medium with number density $n_0 = n(\text{H}) + n(\text{He})$
2. explosion as a large amount of energy released
3. compressing and heating the medium, and setting it into outward motion

$$R_s = 12.8 t_4^{2/5} \left(\frac{E_{51}}{n_0} \right)^{1/5} \quad [\text{pc}] \quad (12.2)$$

$$u_s = 500 t_4^{-3/5} \left(\frac{E_{51}}{n_0} \right)^{1/5} \quad [\text{km s}^{-1}] \quad (12.3)$$

$$T_s = 3.4 \times 10^6 t_4^{-6/5} \left(\frac{E_{51}}{n_0} \right)^{2/5} \quad [\text{K}] \quad (12.4)$$

$$n_s = 4n_0, \quad [\text{cm}^{-3}] \quad (12.5)$$

R_s : radius of the shock front

u_s : shock velocity

T_s : Temperature behind the shock front

n_s : density behind the shock front

t_4 : time since the outburst in units of 10^4 year

E_{51} : energy released by the supernova outburst

12.4 The Cygnus loop

The higher the temperature, the more it ionizes, making [O III] stronger than [O II].

How does a hot, low-density gas in a plasma maintain a specific ionization state?

-> Collision ionization equilibrium

Collision ionization equilibrium

: a state in which the rate at which a specific ion is ionized by electrons is equal to the rate at which ions one level higher recombine with electrons.

In high-temperature gaseous environments, "collision ionization" occurs when atoms or ions collide with surrounding fast electrons, losing electrons and transforming into higher-level ions.

$$n(X^{+i})n_e q_{ion}(X^{+i}, T) = n(X^{+i+1})n_e \alpha_G(X^{+i}, T) [\text{cm}^{-3}\text{s}^{-1}]. \quad (12.6)$$

Left side: Ionization rate

- $n(X^{+i})$: Number (density) of X ions with charge +i per unit volume
- n_e : Density of electrons
- $q_{ion}(X^{+i}, T)$: Collision ionization rate coefficient. This value represents how easily X^{+i} ions change into X^{+i+1} ions by collisions with electrons at temperature T.
- Therefore, the entire left-hand side represents the total rate of ionization of X^{+i} ions into X^{+i+1} ions per unit time and per unit volume.

Right side: recombination rate

- $n(X^{+i+1})$: Density of X ions with charge +i+1
- $\alpha_G(X^{+i}, T)$: Recombination rate coefficient. This represents how easily X^{+i+1} ions combine with electrons to form X^{+i} ions at temperature T.
- Therefore, the entire right-hand side represents the total rate of recombination of X^{+i+1} ions back to X^{+i} ions per unit time and unit volume.

In conclusion, this equation represents the equilibrium condition: "Rate of X^{+i} ions that are ionized and disappear = Rate of X^{+i} ions that are created through recombination."

12.4 The Cygnus loop

$$n(X^{+i})n_e q_{ion}(X^{+i}, T) = n(X^{+i+1})n_e \alpha_G(X^{+i}, T) [\text{cm}^{-3}\text{s}^{-1}]. \quad (12.6)$$

Here $q_{ion}\{X^{+i}, T\}$ is the collisional-ionization rate coefficient

$$q_{ion}(X^{+i}, T) = \int_{\frac{1}{2}mu^2=\chi}^{\infty} u \sigma_{ion}(X^{+i}, u) f(u) du [\text{cm}^3\text{s}^{-1}], \quad (12.7)$$

- $\sigma_{ion}(X^{+i}, u)$: Collision ionization cross section. This refers to the probability of ionization when an electron with velocity u collides with an X^{+i} ion.
- u : Electron velocity.
- $f(u)du$: The fraction of electrons with velocities between u and $u+du$. This is the electron velocity distribution function, which depends on temperature.
- $\int$ (**integral**): This means that the ionization potential is summed over all possible electron velocities.
- **Lower integration limit ($\frac{1}{2}mu^2=\chi$)**: This is the most important part. χ is the minimum energy required for ionization (ionization potential). If the kinetic energy of an electron ($\frac{1}{2}mu^2$) is less than χ , ionization cannot occur even if it collides. Therefore, this integral is calculated only for electrons that are fast enough to ionize.

12.4 The Cygnus loop

Degree of collisional ionization of O

- maximum ionization to O^+ occurs at $T \sim 30,000$ K ($\sim 10^{4.5}$)
- maximum ionization to O^{++} occurs at $T \sim 90,000$ K ($\sim 10^{4.9}$)

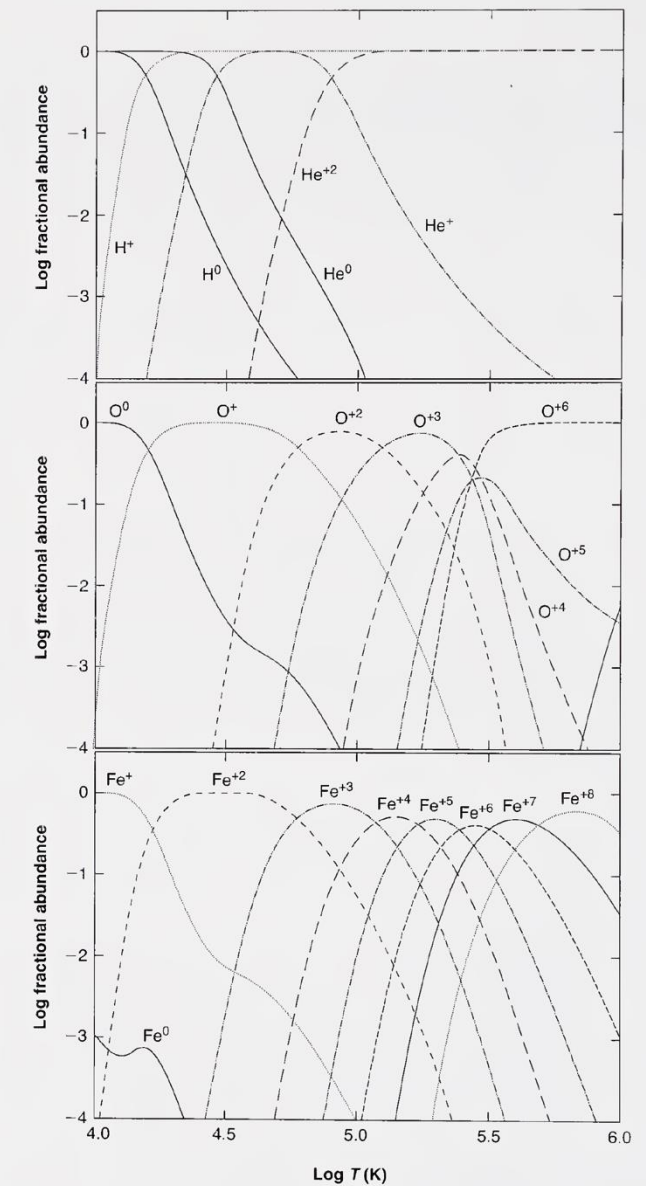


Figure 12.4

Calculated fractional ionization of various ions of H, He, O, and Fe, as functions of temperature for thermal collisional ionization.

degree of collisional ionization as a function of temperature

The physical state and evolution of gas after a shock wave passes through a supernova explosion.

- **Radiation Cooling:**

- Gas heated to millions of degrees by a shock wave does not remain still
- it releases energy through radiation and begins to cool.

- **Non-equilibrium ionization:**

Previously, it was assumed that when a gas is heated, it immediately reaches a "collision ionization equilibrium" state appropriate for its temperature. However, this is not the case.

- **Lag behind:**

In extremely low-density environments, such as supernova remnants, atoms and ions have fewer opportunities to collide with electrons.

➔ This means it takes time for the heated gas to reach an equilibrium state corresponding to its temperature.

In other words, the ionization state lags behind the temperature change, failing to immediately follow the change.

12.4 The Cygnus loop

Comparison with observations of the Cygnus Loop

Complicated situation in reality:

- more complex phenomena occur, such as the "pre-ionization" effect
- "pre-ionization" effect: where high-energy photons ($h\nu > 13.6 \text{ eV}$) emitted just ahead of the shock wave ionize the gas before the shock wave arrives.

The Cygnus Loop's multi-temperature structure:

- [O III] emission: Emitted primarily at temperatures around 30,000 K.
- [N II] emission: Emitted from cooler regions at around 10,000 K.
- X-ray emission: Emitted from very hot gas at temperatures between 1 and 3 million K.
- Highly ionized iron ([Fe X], [Fe XIV]) emission: Observed from regions of very hot, tenuous gas that are optically invisible.

The observation of emission lines at such a wide range of temperatures suggests that the Cygnus Loop is not a structure with a single temperature, but rather a complex temperature distribution.

Inhomogeneous interstellar medium model:

To explain this complex structure, a model has been proposed in which supernovae exploded not in a homogeneous space, but in denser (about 10 cm^{-3}) gas clouds ("clouds") nestled within a less dense medium (about 0.2 cm^{-3}).

- In regions of low density:** The shock wave travels rapidly, heating the gas to high temperatures, emitting mainly X-rays.
- In regions of high density:** The shock wave slows down, and the gas cools more rapidly, emitting more intense optical lines (e.g., [O III], [N II]).

Filament Structure and Total Mass

- **Identity of the Filaments:**
 - not actually thin, thread-like structures, but rather thin sheets of material that appear edge-on when viewed from the shock front.
- **Mass of Swept-Up Interstellar Material:**
 - The total mass of interstellar material swept up by the shock wave within the Cygnus Loop is estimated to be between 100 and 1,000 times the mass of the Sun (10^2 to $10^3 M_{\odot}$).
- **Comparison with supernova ejecta:**
 - This mass is much greater than the mass ejected from the star itself in the supernova explosion.
 - most of the Cygnus Loop we see today is likely interstellar matter from the original region
 - with the original debris of the star likely remaining somewhere in the core.
- **Sun-like elemental abundance:**
 - The abundance of elements observed in the filaments is nearly identical to that of the Sun
 - It provides strong evidence that this gas is not material from the supernova itself, but rather is mostly normal interstellar matter that was there from the beginning.

12.5 Cas A

Cas A

- The youngest known supernova remnant in our galaxy
- A powerful radio source
- Synchrotron emission:
 - This suggests the presence of a strong magnetic field and high-energy particles within Cas A

Optical/X-ray observations (Figure 12.5):

- **Optical image (left):**
 - Seen in hydrogen ($H\alpha$) and nitrogen ($[N II]$) light,
 - it appears as scattered, reddish "bits," "streaks," and "knots."
 - These are partially obscured by interstellar dust.
- **X-ray image (right):**
 - taken by the Chandra X-ray Observatory
 - is a composite of several images covering the 0.3–10 keV energy range.
 - Because X-rays are highly penetrable through gas and dust, they clearly reveal the overall spherical structure of the remnant, which is not visible in the optical image.

Optical

X-ray

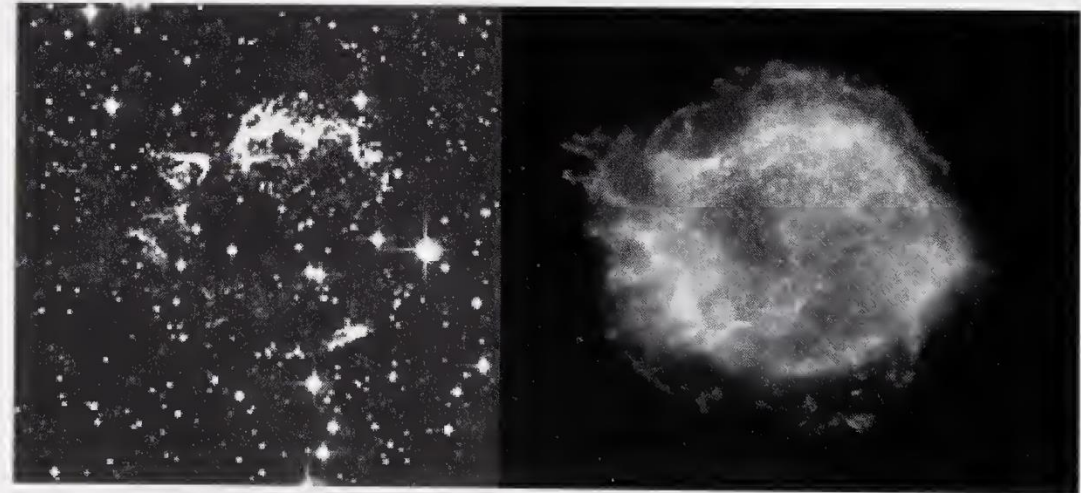


Figure 12.5

Cas A in the optical (left) and X-ray. The optical image was taken in the light of $H\alpha + [N II]$. The X-ray image is a composite of images taken in the energy range 0.3 to 10 keV. The optical image is heavily obscured by intervening interstellar matter. X-rays penetrate through the gas and dust much more easily, so this image shows the full nebula. The remnant has an apparent radius of $2'$, which corresponds to a radius of 1.7 pc for an assumed distance of 3.4 kpc.

12.5 Cas A

2. Cas A's Expansion and Two Types of Ejecta

- Cas A's ejecta can be broadly divided into two types
- providing important clues to understanding the star's structure and evolution before its explosion.

Fast-moving knots (FMKs)

- Characteristics:
 - expanding at extremely high velocities, reaching up to 5,600 km/s.
- Unique Chemical Composition:
 - The spectra of these knots are unusual
 - lack any hydrogen (H) or helium (He) emission lines.
 - strong oxygen ([O I], [O II], [O III]), sulfur ([S II]), and argon ([Ar III]) lines.
- Origin:
 - knots are nearly pure chunks of oxygen, with traces of other heavy elements.
 - they were formed by nuclear fusion deep in the star's core, ejected during the supernova explosion.
 - explosion occurred after the hydrogen and helium in the star's outer layers had already been blown away.

Quasi-stationary flocculi (QSFs)

- Characteristics:
 - velocity of about 150 km/s, much slower than FMKs
 - appear to be almost stationary, but they actually travel much faster than the surrounding interstellar medium.
- Chemical composition:
 - rich in hydrogen (H), helium (He), and nitrogen (N).
 - nitrogen content is about 10 times higher than that of typical interstellar medium.
- Origin:
 - interpreted as clumps of material ejected by a star as a stellar wind before a supernova explosion
 - material from the outer layers of the star first spread out into space and formed a clump, and then the shock wave from the explosion at the center struck these clumps, causing them to glow.

3. Stellar Structure and Evidence for Nucleosynthesis Theory

Layered Structure:

X-ray observations reveal a layered shell structure in the Cas A remnant.

- **Brightest Knots:**

- The optically brightest and densest knots are composed primarily of oxygen and sulfur, with little iron (Fe),
- indicating their origin in the stellar mid-layer.

- **Dark Regions:**

- Relatively dark regions are found to contain both sulfur and silicon (Si)
- significant amounts of iron (Fe).

Verification of Nucleosynthesis Theory:

- spatial distribution of these elements: nuclear fusion occurring in the final stages of stellar evolution.
- it is consistent with the theory that heavier elements (iron) are produced toward the center of a star, while lighter elements (oxygen and sulfur) are present in the outer layers.

Conclusion

- Cas A is a complex and dynamic object, where the stellar interior (FMKs) and previously ejected outer material (QSFs) interact with each other due to the supernova explosion.
- By studying the velocity, chemical composition, and spatial distribution of each ejecta, we can gain valuable information about the star's final stages and the element formation processes occurring within it.