Stellar Atmosphere

Reading assignment

TUESDAY 10/20: Chapter 10.1 / 10.2 / 16.3

Homework Assignment #3 due by:

TUESDAY 10/27 before beginning of class

The Pressure Integral:

The microscopic source of pressure in a perfect gas is particle bombardment, resulting in transfer of momentum, hence a force (F=dp/dt). The average force per unit of area is the PRESSURE.

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number density of particles w/ momentum p in the range dp

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NOTE: the relation between p and v_p depends upon relativistic considerations, whereas n(p) depends on the type of particles and quantum statistics.

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$$F_\lambda = \frac{2\pi c^2 h}{\lambda^5} \frac{1}{e^{hc/\lambda KT} - 1} \longleftrightarrow F_\nu = \frac{2\pi h \nu^3}{c^2} \frac{1}{e^{h\nu/KT} - 1}$$

[erg s^{-1} cm^{-2} A^{-1}]

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ENERGY DENSITY $$u := \int_0^\infty u(\nu)\,d\nu = \frac{8\pi^5 K^4}{15\,c^3 h^3} T^4 = a T^4$$

w/ $a = 7.565 \times 10^{-15} \frac{\text{erg}}{\text{cm}^3\,\text{K}^4}$

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$$\longrightarrow \underbrace{n}_{\text{number density}} := \int_0^\infty n_\lambda \, d\lambda = 8\pi \left(\frac{KT}{hc}\right)^3 \underbrace{\int_0^\infty \frac{x^2\,dx}{e^x - 1}}_{2.404114} = 19.232912\pi \left(\frac{KT}{hc}\right)^3$$

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$$u = a T^4$$

$$\Rightarrow P_R = \frac{1}{3} u = \frac{1}{3} a T^4$$

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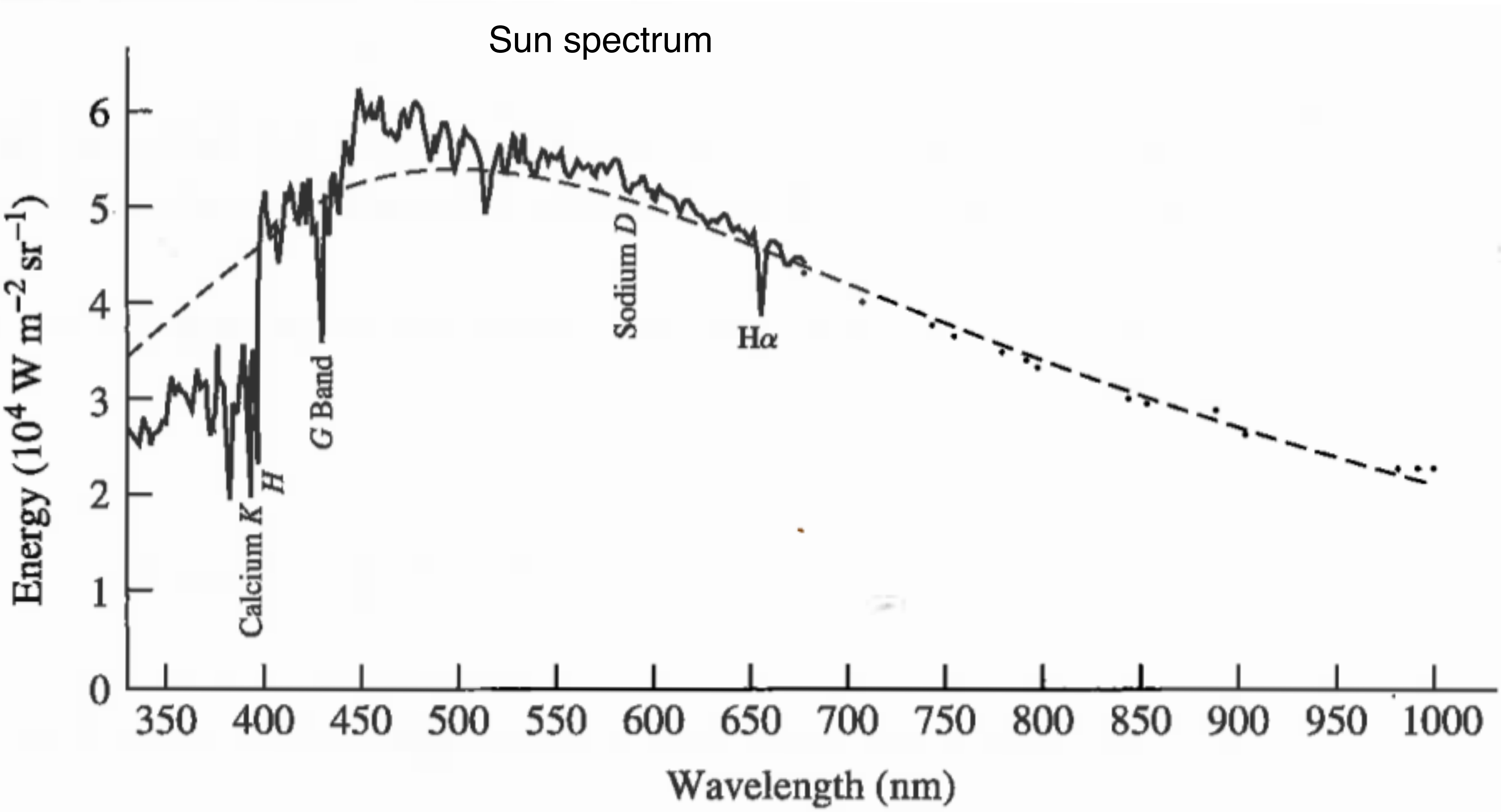
Radiation pressure for a blackbody radiation

Stellar Opacity



The Sun spectrum deviates substantially from the shape of the blackbody Planck function due to solar absorption lines removing light from the Sun's continuous spectrum (a.k.a., line blanketing)

A star cannot be in THERMODYNAMIC EQUILIBRIUM (no net flow of energy through the box or between matter and radiation; every process occurs at the same rate as its inverse process), as a net flow (outward) of energy occurs through the star, and the temperature varies with location. However, the idealized case of a single temperature can still be employed IF the distance over which the temperature changes significantly is larger compared with the distances traveled by particles and photons between collisions/ interactions (mean free paths). In this case, we define **LOCAL THERMODYNAMIC EQUILIBRIUM (LTE)**.

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TEMPERATURE SCALE HEIGHT

$$H_T := \frac{T}{|dT/dr|} = \frac{5685\,°K}{(5790-5580)/25} = 677\ km$$

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Characteristic distance over which the temperature varies

$\rho = 2.1 \times 10^{-4} \frac{kg}{m^3}$ Mass density of photosphere, primarily made of H in the ground state

$n = \rho / m_H = 1.25 \times 10^{23} \ m^{-3}$ Number density of atoms

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i.e., the atoms see a constant kinetic temperature between collisions, hence LTE is valid for H atoms in the photosphere

Consider now a beam of parallel light rays traveling through a gas; absorption is the ensemble of processes of removing photons (including scattering).

For pure absorption, the intensity declines exponentially falling by a factor of e^{-1} over a characteristic distance:

$$\ell = \frac{1}{\kappa_\lambda \rho}$$

w/ κ_λ opacity (or absorption coefficient)

$[\kappa_\lambda] = m^2/Kg$

cross section for absorbing photons of wavelength λ per unit of mass of stellar material.

In the photosphere: $\kappa_{500nm} = 0{,}03 \, \frac{m^2}{Kg} \rightarrow \ell = 160 \text{ Km}$

NOT TOO DIFFERENT FROM $H_T \simeq 677$ Km

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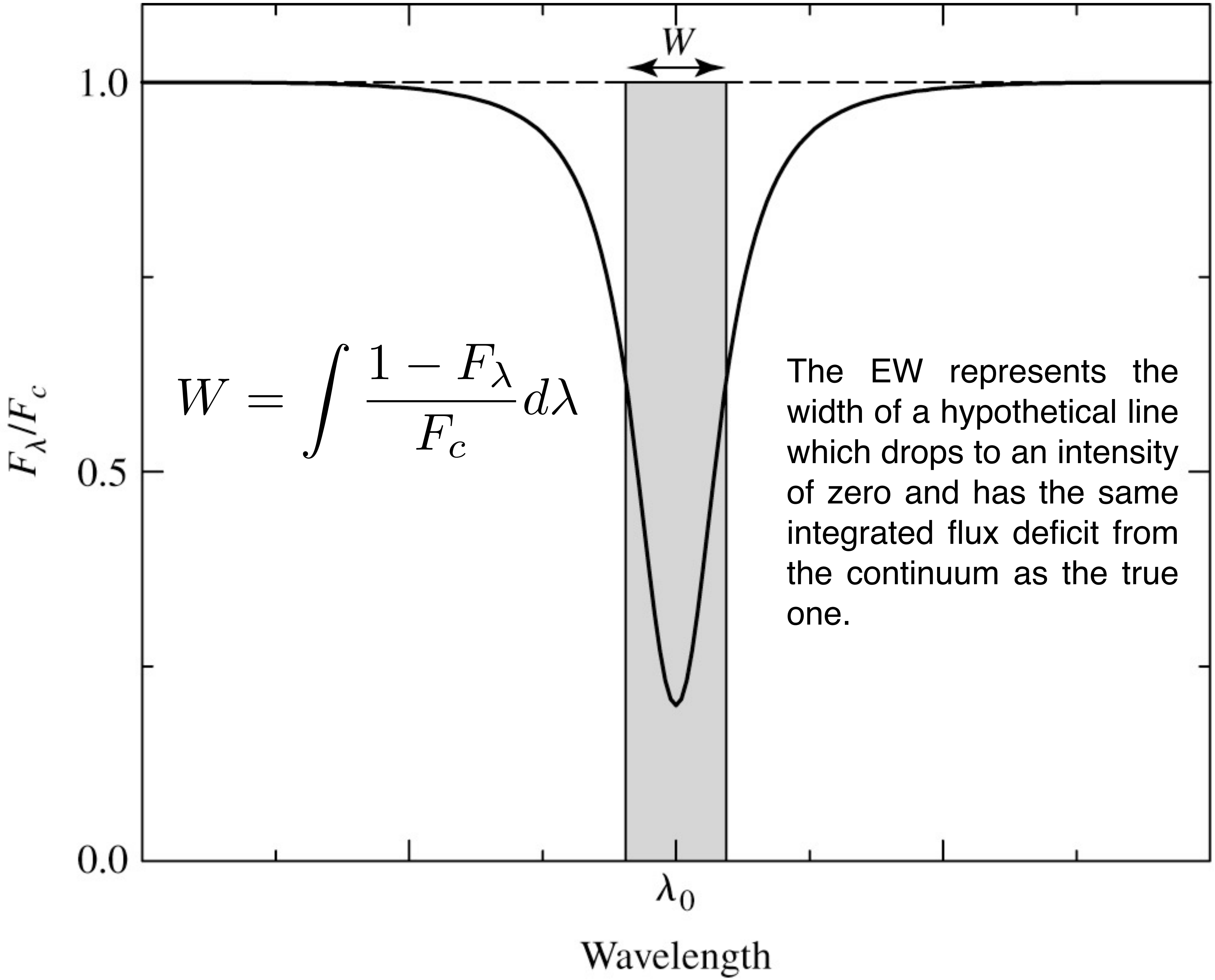
NOT TOO DIFFERENT FROM $H_T \simeq 677\ km$

i.e., the photospheric photons do not see a constant temperature, and so LTE is not strictly valid in the photosphere. LTE must be used with caution in stellar atmosphere.

Equivalent width (EW, or W) of spectral line



$$W = \int \frac{1 - F_\lambda}{F_c} d\lambda$$

The EW represents the width of a hypothetical line which drops to an intensity of zero and has the same integrated flux deficit from the continuum as the true one.

Let N be the column density (i.e., m^{-2}), i.e., the number of atoms of a certain element lying above a unit area of the photosphere.

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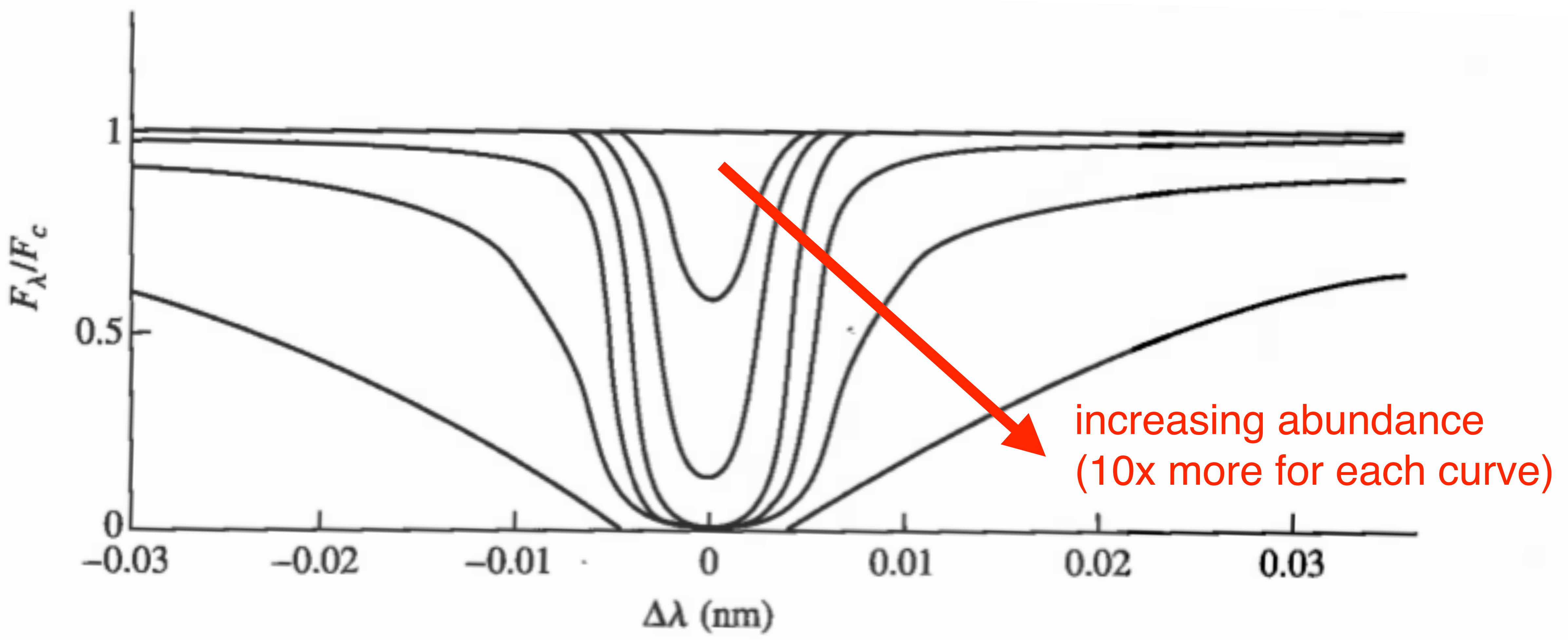
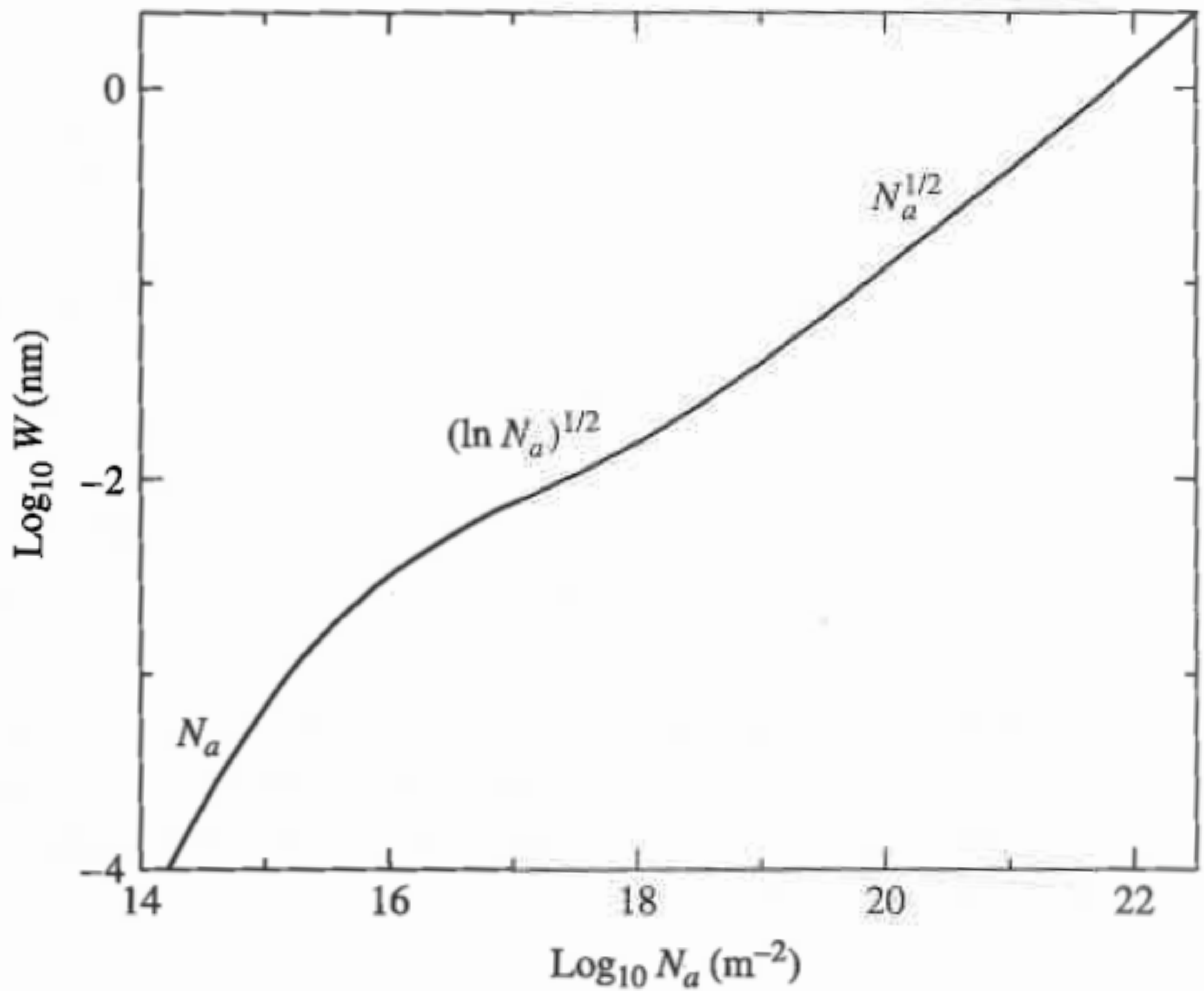
fN_a = effective number of atoms lying above each square meter of photosphere actively involved in producing a given spectral line

Growth curve method

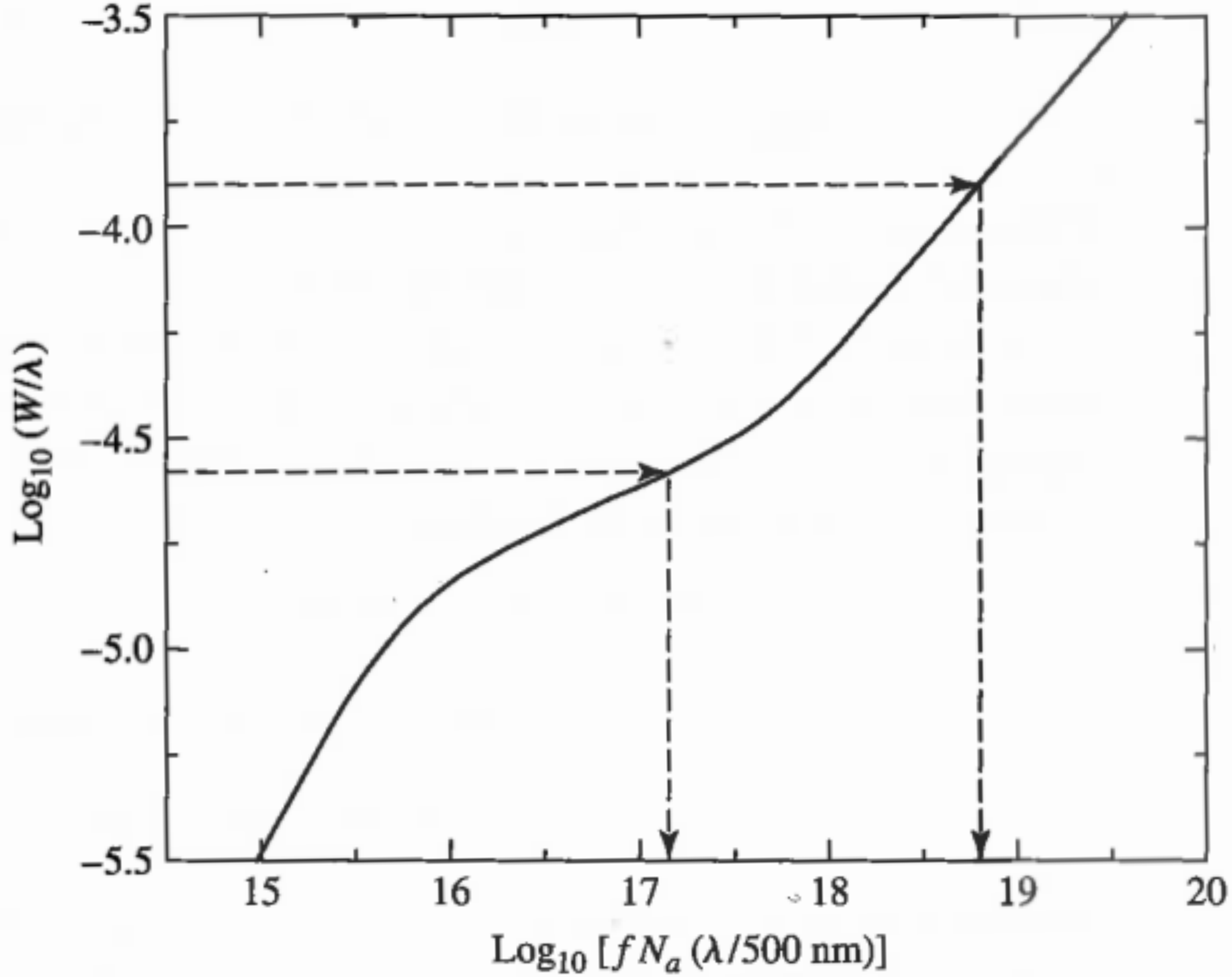


This is used to determine the value of N_a, hence the abundances of elements in the stellar atmosphere.

Variation of the EW of an absorption line with increasing N_a (a.k.a., **curve of growth**)



For small abundances, when the absorption line is has not saturated, EW is proportional to N_a. In the central region is when the line saturates and the EW changes little because of only the wings becoming deeper and so little change in the EW. Increasing Na even further increases the importance of pressure broadening, and the wings are significantly affected, with the EW growing as $N_a^{1/2}$.



For a given element, the EW is measured from the spectrum (e.g., of the Sun). Using the appropriate curve of growth, I can obtain fN_a. Known fN_a and f, I can derive the total number of atoms of a specific element using the Boltzmann and Saha equations.

Repeating this for many elements, transitions, **I can derive the chemical composition of the photosphere of stars**.

TABLE 9.2 The Most Abundant Elements in the Solar Photosphere. The relative abundance of an element is given by $\log_{10}(N_{el}/N_H) + 12$. (Data from Grevesse and Sauval, *Space Science Reviews*, *85*, 161, 1998.)

Element	Atomic Number	Log Relative Abundance	**Relative abundance by number**
Hydrogen	1	12.00	
Helium	2	10.93 ± 0.004	8.5% N_H
Oxygen	8	8.83 ± 0.06	0.068% N_H
Carbon	6	8.52 ± 0.06	0.033% N_H
Neon	10	8.08 ± 0.06	0.012% N_H
Nitrogen	7	7.92 ± 0.06	
Magnesium	12	7.58 ± 0.05	
Silicon	14	7.55 ± 0.05	
Iron	26	7.50 ± 0.05	
Sulfur	16	7.33 ± 0.11	
Aluminum	13	6.47 ± 0.07	
Argon	18	6.40 ± 0.06	
Calcium	20	6.36 ± 0.02	0.00023% N_H
Sodium	11	6.33 ± 0.03	
Nickel	28	6.25 ± 0.04	

Isotope	A	mass fraction in parts per million	number fraction in parts per million
Hydrogen-1	1	705,700	909,964
Hydrogen-2	2	23	15
Helium-3	3	35	15
Helium-4	4	275,200	88,714
Carbon-12	12	3,032	326
Carbon-13	13	37	4
Nitrogen-14	14	1,105	102
Oxygen-16	16	5,920	477
Neon-20	20	1,548	100
Neon-22	22	208	12
Sodium-23	23	33	2
Magnesium-24	24	513	28
Magnesium-25	25	69	4
Magnesium-26	26	79	4
Aluminum-27	27	58	3
Silicon-28	28	653	30
Silicon-29	29	34	2
Silicon-30	30	23	1
Sulfur-32	32	396	16
Argon-36	36	77	3
Calcium-40	40	60	2
Iron-54	54	72	2
Iron-56	56	1,169	27
Iron-57	57	28	1
Nickel-58	58	49	1
Other elements:		3,879	149

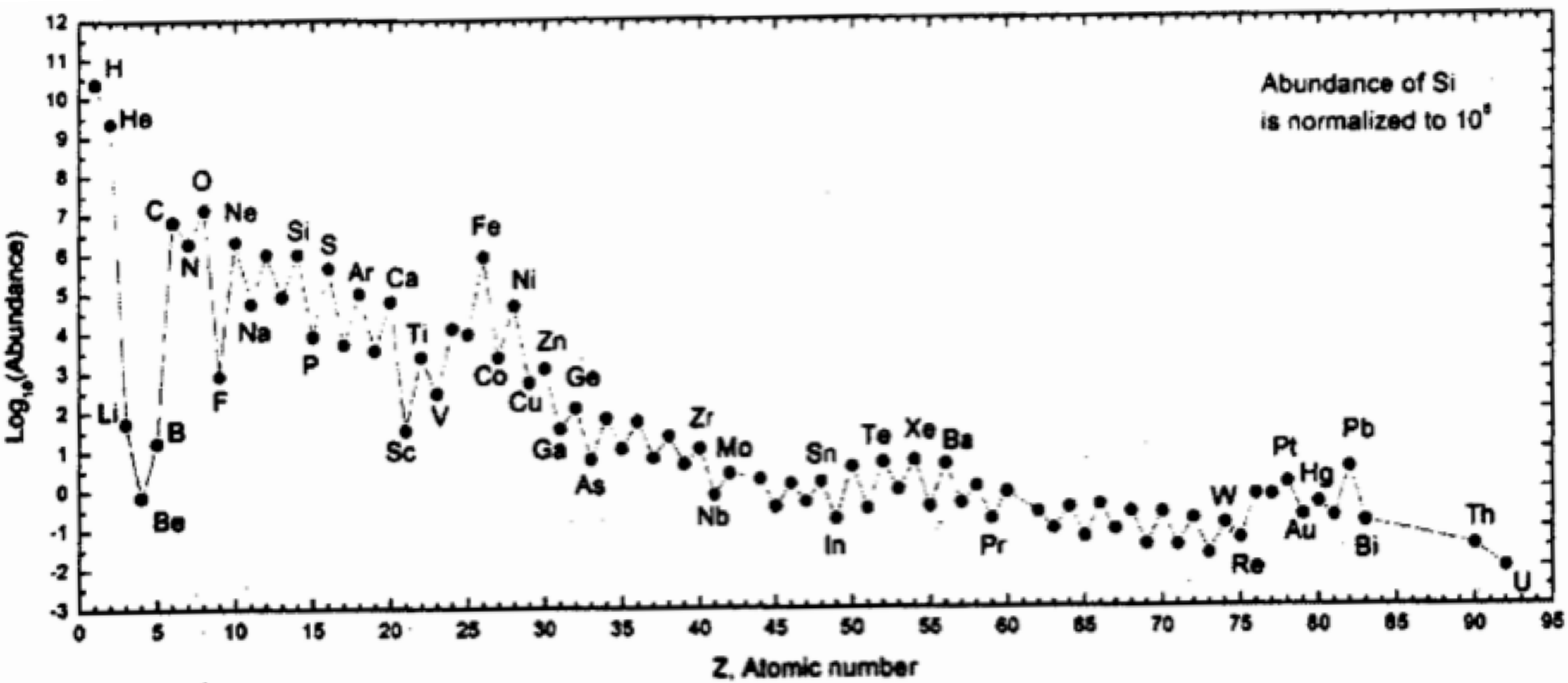
H-1: 705700/1000000 = 0.7057 = 70.6%

He-4: 275200/1000000 = 0.2752 = 27.5%

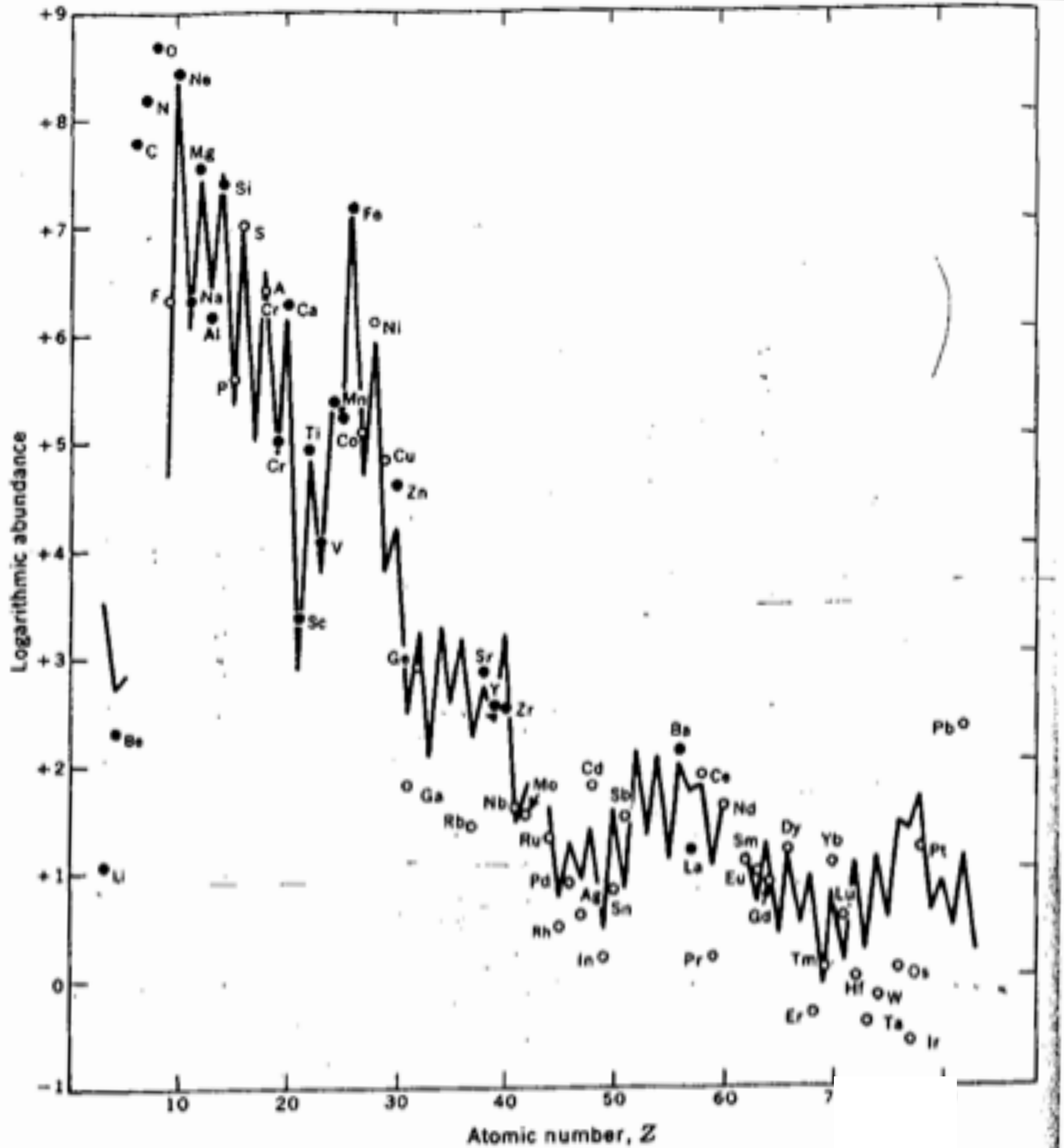
Metals: 198100/1000000 = 0.0191 = 1.9%

$$\frac{A\frac{N_{elem}}{N_H}}{1 + A\frac{N_{elem}}{N_H}}$$

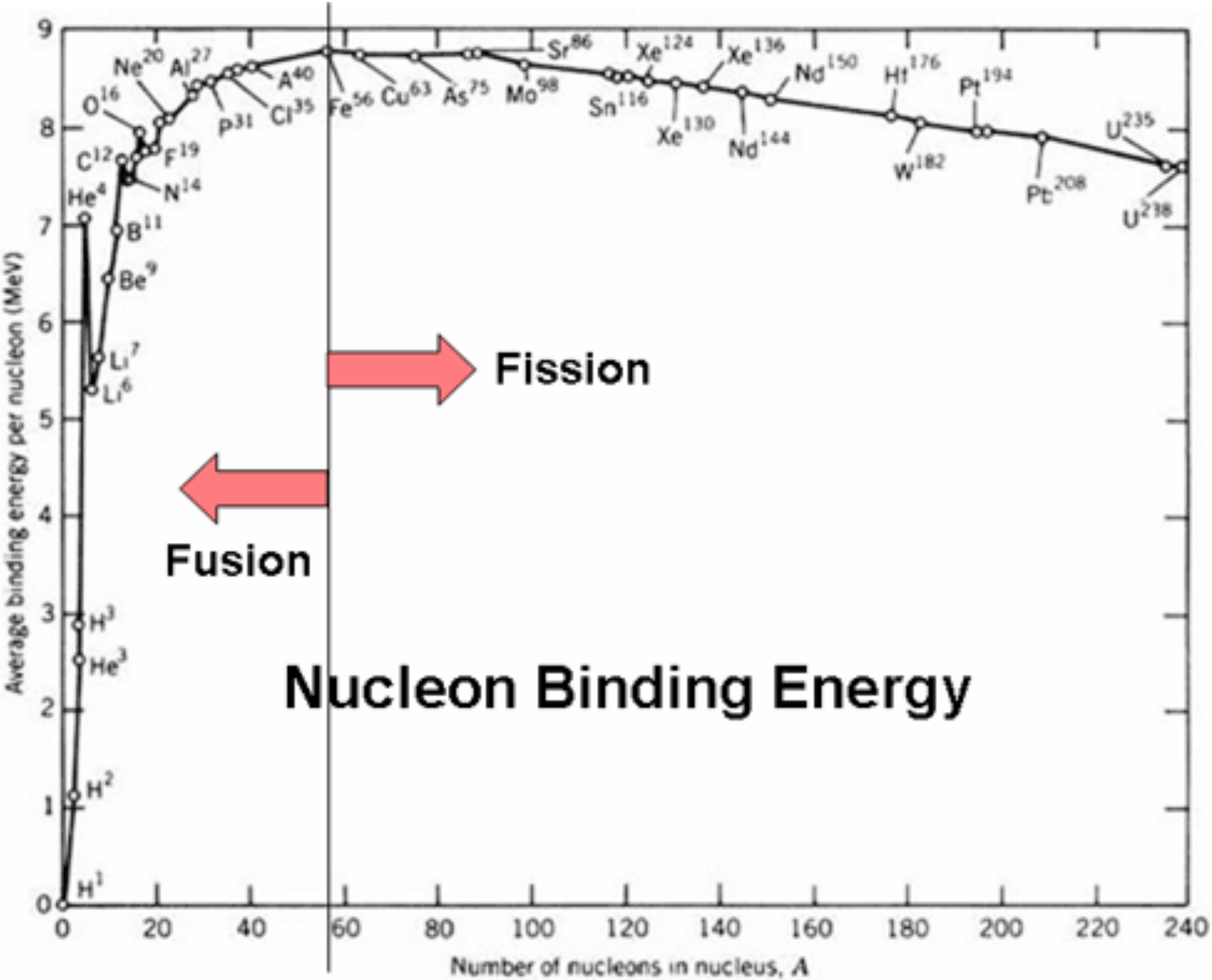
A = mass number



Abundance of Si
is normalized to 10^6
Log10(Abundance)
Z, Atomic number
H
He
Li
Be
B
C
N
O
F
Ne
Na
Si
P
S
Ar
Ca
Sc
Ti
V
Fe
Co
Ni
Cu
Zn
Ga
Ge
As
Zr
Nb
Mo
Sn
In
Te
Xe
Ba
Pr
W
Re
Pt
Au
Hg
Pb
Bi
Th
U



Logarithmic abundance
Atomic number, Z
+9
+8
+7
+6
+5
+4
+3
+2
+1
0
−1
10
20
30
40
50
60
O
Ne
N
C
Mg
Si
S
Fe
F
Na
A
Cr
Ca
Al
Ni
P
Mn
Co
Ti
Cr
Cu
Zn
V
Sc
Ge
Sr
Y
Zr
Be
Li
Ga
Rb
Nb
Mo
Cd
Sb
Ba
Ce
Nd
Ru
Pd
Ag
Sn
Rh
In
La
Pr
Sm
Eu
Gd
Dy
Yb
Lu
Tm
Er
Hf
W
Ta
Os
Ir
Pt
Pb


Fission
Fusion
Nucleon Binding Energy
Average binding energy per nucleon (MeV)
Number of nucleons in nucleus, A
H1
H2
H3
He3
He4
Li6
Li7
Be9
B11
C12
N14
O16
F19
Ne20
Al27
P31
Cl35
A40
Fe56
Cu63
As75
Sr86
Mo98
Sn116
Xe124
Xe130
Xe136
Nd144
Nd150
Hf176
W182
Pt194
Pt208
U235
U238

NUCLEOSYNTHESIS:

- Nucleosynthesis occurs in the natural evolution of stars
- The initial H and He are fused into heavier nuclei, dispersed in the ISM in the terminal phases of stellar evolution
- During the first 3 minutes after the Big Bang, H (75% by mass), He (25%) and traces of D, ^{3}He, Li, Be, B were produced (primordial nucleosynthesis)
- ^{12}C, ^{16}O, ^{20}Ne most abundant elements after H and He (produced by He fusion)
- ^{56}Fe: nuclear binding energy per nucleon has a maximum at ^{56}Fe, i.e., successive nuclear fusion reactions cease to liberate energy when all light nuclei have been fused into ^{56}Fe. Farther fusion requires energy, hence the termination of energy-generating stages of nuclear fusion.
- Very heavy elements can be formed efficiently by the capture of free neutrons liberated as a by product of reactions between light charged particles.

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