Measuring Stellar Elemental Abundance

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Motivation

Why measure Stellar Abundances?

- ⋆ Elemental abundances can reveal star's composition, formation history, and evolutionary state
- ⋆ Can help refine models of nucleosynthesis and galactic chemical evolution

Why Sodium (Na)?

- ⋆ Absorption lines and stellar spectra are relatively easy to observe and analyze

The Broader Impact:

- ⋆ This same methodology applies to other elements (Fe, Mg, Si) , expanding our understanding of stellar chemistry
- ⋆ Compositions of host stars can be reflected in **orbiting exoplanets**

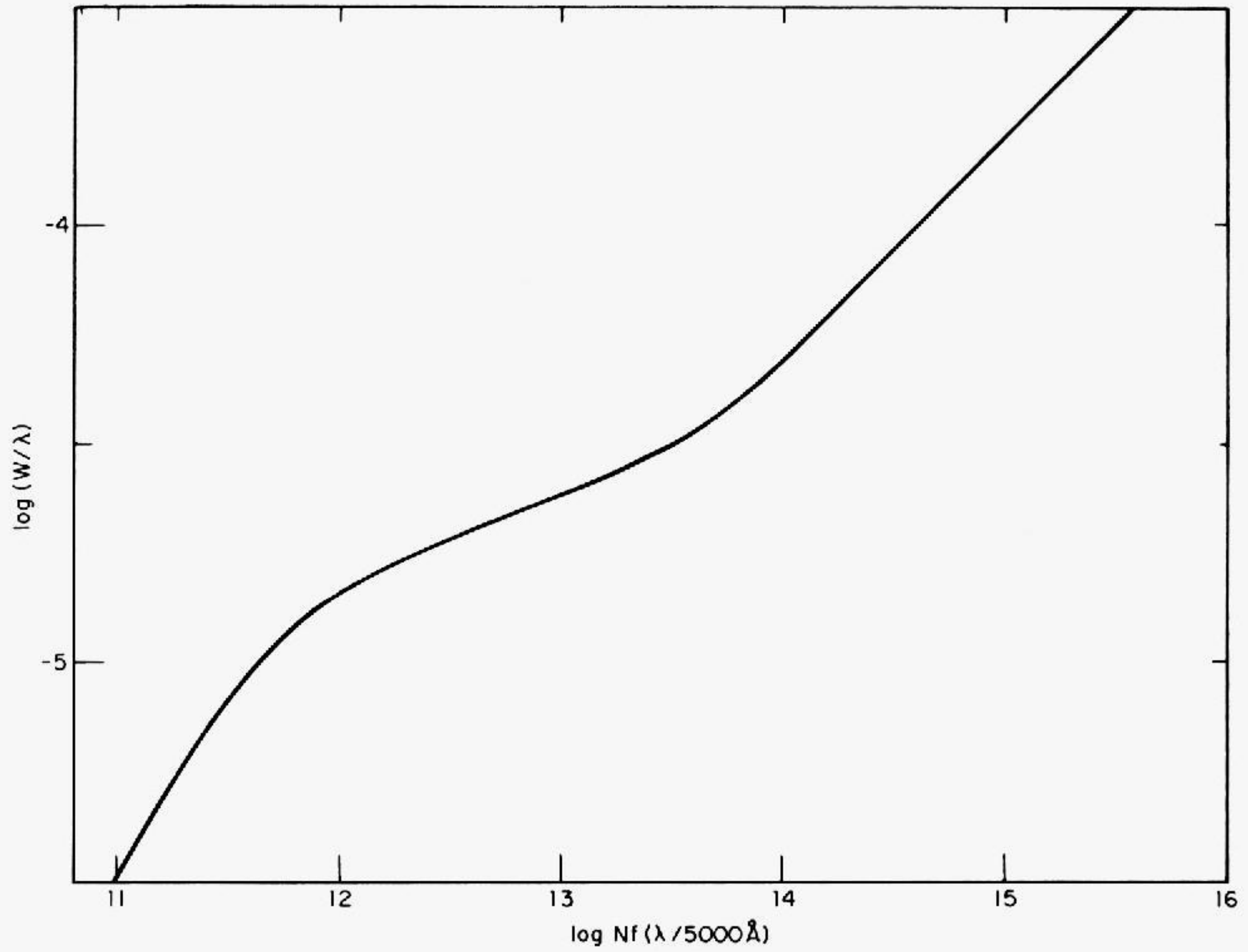

Figure 9.22 A general curve of growth for the Sun. (Figure from Aller, *Atoms, Stars, and Nebulae*, Revised Edition, Harvard University Press, Cambridge, MA, 1971.)

Above is a section of the spectrum of neutral sodium, produced when the sodium atom jumps from the ground state 3s to the excited state 3p

Methods

Measuring Equivalent Width of Na I Line

- ⋆ Identified doublet and measured its EW
- ⋆ Used curve of growth to determine the column density of Na in absorbing state

1. Excitation State Ratio (Boltzmann Equation)

- ⋆ Used Boltzmann Eq to calculate ratio of excited to ground state atoms

$$\frac{N_2}{N_1} = \frac{g_2}{g_1} \exp\left(-\frac{E_2 - E_1}{kT}\right)$$

Parameters:

g1 = 2 (number of separate)
g2 = 6
E1 = -5.14 eV
E2 = -3.04 eV
T = 5778 Kelvin

2/3. Ionization Ratio (Saha Equation)

- ⋆ Applied Saha Eq to determine the ratio of ionized to neutral Na

$$\frac{Na_{II}}{Na_{I}} = \frac{2kT}{P_e} - \frac{Z_{II}}{Z_I} \left(\frac{2\pi m_e kT}{h^2}\right)^{3/2} \exp\left(-\frac{\chi}{kT}\right)$$

Parameters:

ZI = 2.4 (partiton function)
ZII = 1.0
Pe = 1.0N x m^-2
X = 5.1 eV (ionization energy)

Methods

4. **Total Column Density of Na**

    ⋆ Combined results from the curve of growth, Boltzmann Eq, and Saha Eq

$$N_1 \times \left(1 + \frac{N_2}{N_1}\right) \times \left(1 + \frac{Na_{II}}{Na_I}\right)$$

Parameters:
N1 = 8.24E14
N2/N1 = 0.044
NaII/NaI = 2510.75

5. **Relative Abundance of Na to H**

    ⋆ Compared to hydrogen column density (N_H 6.6E23 atoms/cm_2

    ⋆ Number ratio: N_{Total}/N_H and [Na/H]

Parameters:
Na_total = 2.16E18 atoms/cm^2

Astronomers' Notation: $12 + \log_{10}\left(\frac{N_{element}}{N_H}\right)$

Results

Quantity	Symbol	Value	Units
Ratio of excited to ground state Na atoms	$\frac{N_2}{N_1}$	0.044 A	---
Ratio of ionized to neutral Na atoms	$\frac{N_{NaII}}{N_{NaI}}$	2510.75 B	---
Total column density of Na atoms	Na_{total}	2.161E18	Atoms/cm^2
Relative abundance of Na to H	$\frac{N_{Na}}{N_H}$	3.27E-6	Atoms/cm^2
Logarithmic abundance of Na relative to H	[Na/H]	7.87	Atoms/cm^2

A. For every Na atom in the excited state, there are about 22.624 atoms in ground state
B. For every ionized Na atom, there are about 0.0004 neutral atoms

Conclusions

Measured Sodium Abundance in the Sun

★ Determined the number density of sodium in different states using curve of growth, Boltzmann equation, and Saha equation

★ Calculated the total sodium column density in the solar photosphere

Sodium's Ionization and Excitation behavior

★ Found that only a small fraction of sodium atoms are in the excited state

★ Determined the ionization balance of sodium, showing relative proportions of neutral and ionized Na

Relative Abundance of Sodium to Hydrogen

★ Calculated N_{Na}/N_H and [Na/H], reporting results in both physicists' and astronomers' notation

★ Confirmed that sodium is a trace element compared to hydrogen but plays a key role in stellar spectroscopy

Broader Implications

★ The same methodology can be applied to other elements (e.g., Fe, Mg, Si) to understand stellar composition

★ These techniques are essential for studying **stellar atmospheres, chemical evolution, and exoplanet atmospheres**