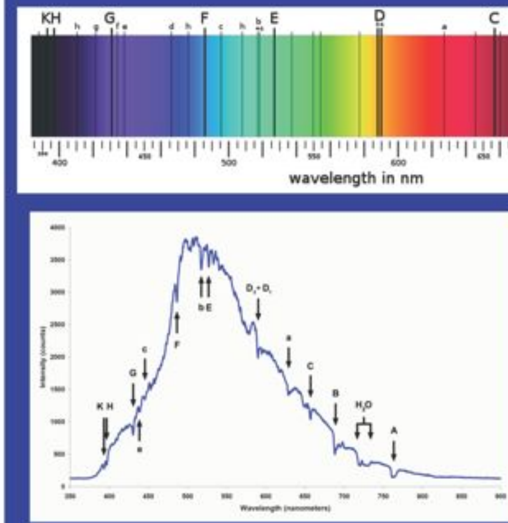
Lecture 3

Atomic Spectroscopy and Abundances

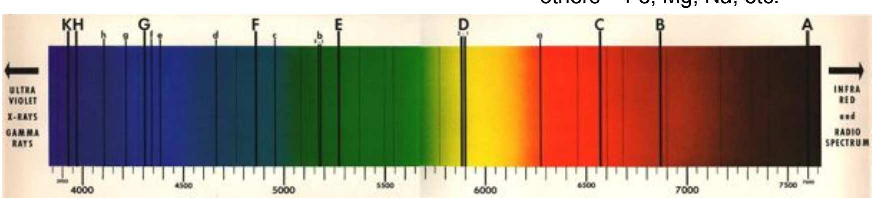
Glatzmaier and Krumholz 1
Pols 3.5.1



Solar spectrum, shown as through a prism (top) and in a plot of intensity vs. wavelength (side) (images taken from wikipedia)

The solar spectrum

C = Balmer alpha
F = Balmer beta
f = Balmer gamma
B = oxygen
D = sodium
E = iron
H, K = singly ionized calcium
others = Fe, Mg, Na, etc.



Wollaton (1802) discovered dark lines in the solar spectrum. Fraunhaufer rediscovered them (1817) and studied the systematics.

Note D, H, K stronger tha C, F, f but the sun is not made of Na and Ca,

Fraunhofer's Notation

Die wichtigsten Fraunhoferlinien im Überblick

Symbol	Element	Wellenlänge in nm	Symbol	Element	Wellenlänge in nm
y	O_2	898,765	c	Fe	495,761
Z	O_2	822,696	F	H β	486,134
A	O_2	759,370	d	Fe	466,814
B	O_2	686,719	e	Fe	438,355
C	H α	656,281	G'	H γ	434,047
a	O_2	627,661	G	Fe	430,790
D_1	Na	589,594	G	Ca	430,774
D_2	Na	588,997	h	H δ	410,175
D_3 oder d	He	587,562	H	Ca^+	396,847
e	Hg	546,073	K	Ca^+	393,368
E_2	Fe	527,039	L	Fe	382,044
b_1	Mg	518,362	N	Fe	358,121
b_2	Mg	517,270	P	Ti^+	336,112
b_3	Fe	516,891	T	Fe	302,108
b_4	Fe	516,751	t	Ni	299,444
b_4	Mg	516,733			

discovery of He in the sun Lockyer 1868

Quantum mechanics tells us:

Radiation in the form of a single quantum (photon) is emitted (or absorbed) when an electron makes a transition from one energy state to another in an atom. The energy of the photon is the difference between the energies of the two states.

E.g., for hydrogen-like atoms

emission $\quad$ absorption

$$\mathrm{E}_m \rightarrow \mathrm{E}_n + h\nu \qquad (\text{or } \mathrm{E}_n + h\nu \rightarrow \mathrm{E}_m) \qquad m > n$$

$$h\nu = \frac{hc}{\lambda} = E_m - E_n$$

$$\frac{1}{\lambda} = \frac{E_m - E_n}{hc} = \frac{2\pi^2 Z^2 e^4 m_e}{h^3 c}\left(\frac{1}{n^2} - \frac{1}{m^2}\right)$$

$$\frac{1}{\lambda_{mn}} = 1.097\times10^5\ Z^2\left(\frac{1}{n^2} - \frac{1}{m^2}\right)\ \mathrm{cm}^{-1}$$

$$\boxed{\lambda_{mn} = \frac{911.6}{Z^2}\left(\frac{1}{n^2} - \frac{1}{m^2}\right)^{-1}\ \text{Angstroms}}$$

(for atoms with only one electron)

$$\boxed{\lambda_{mn} = \frac{911.6\ \mathrm{A}}{Z^2}\left(\frac{1}{n^2} - \frac{1}{m^2}\right)^{-1}}$$

E.g.,

$m=2,\ \ n=1,\ \ Z=1$

$$\lambda = 911.6\ \mathring{\mathrm{A}}\left(\frac{1}{1^2} - \frac{1}{2^2}\right)^{-1} = 911.6\left(\frac{3}{4}\right)^{-1}$$

$$= 911.6\left(\frac{4}{3}\right) = 1216\,\mathring{\mathrm{A}}$$

$m=3, n=1, Z=1$

$$\lambda = 911.6\left(\frac{1}{1^2} - \frac{1}{3^2}\right)^{-1} = 911.6\left(\frac{8}{9}\right)^{-1}$$

$$= 911.6\left(\frac{9}{8}\right) = 1026\,\mathring{\mathrm{A}}$$

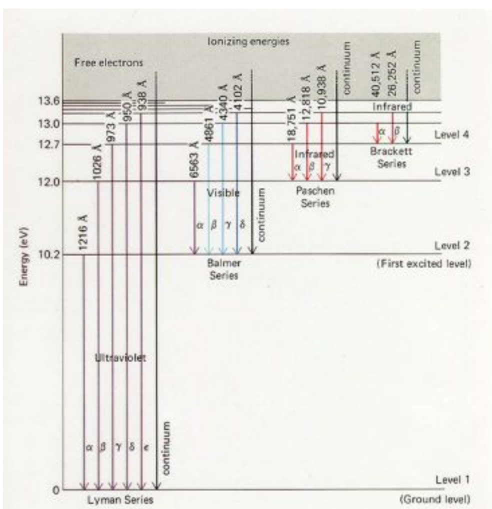
Lines that start or end on n=1 are called the “Lyman” series. All are between 911.6 and 1216 A.

$m=3, n=2, Z=1$

$$\lambda = 911.6\left(\frac{1}{2^2} - \frac{1}{3^2}\right)^{-1} = 911.6\left(\frac{1}{4} - \frac{1}{9}\right)^{-1}$$

$$= 911.6\left(\frac{5}{36}\right)^{-1} = 911.6\left(\frac{36}{5}\right) = 6563\,\mathring{\mathrm{A}}$$

Lines that start or end on n=2 are called the “Balmer” series. All are between 3646 (i.e. 4*911.6) and 6564 A.

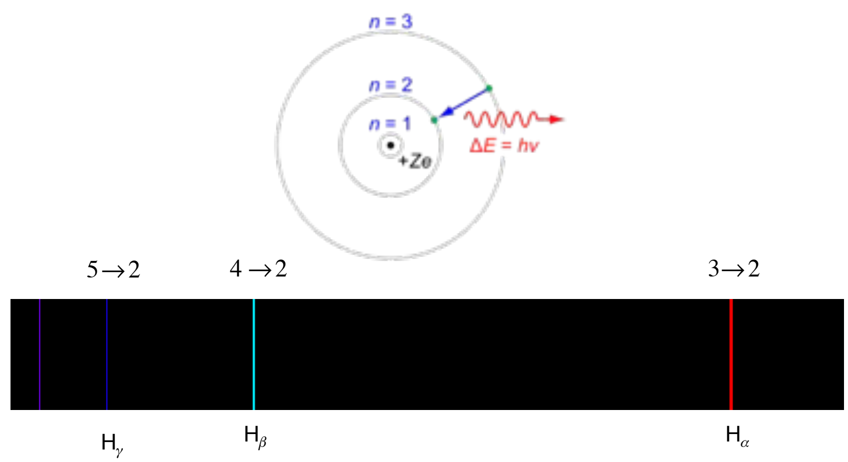


$H_{\alpha,\beta,\gamma,\ldots\ldots}$

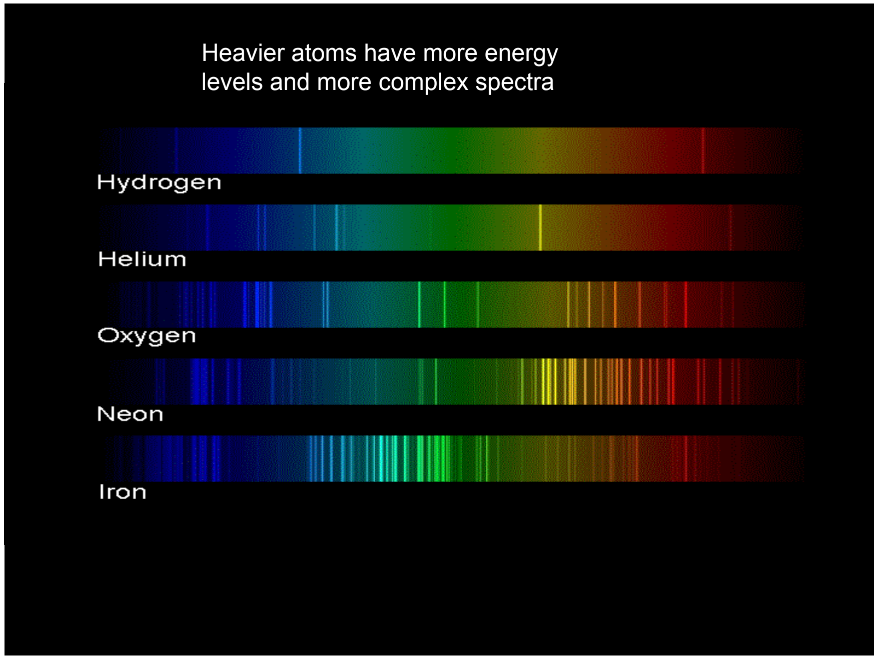
$Ly_{\alpha,\beta,\gamma,\ldots}$

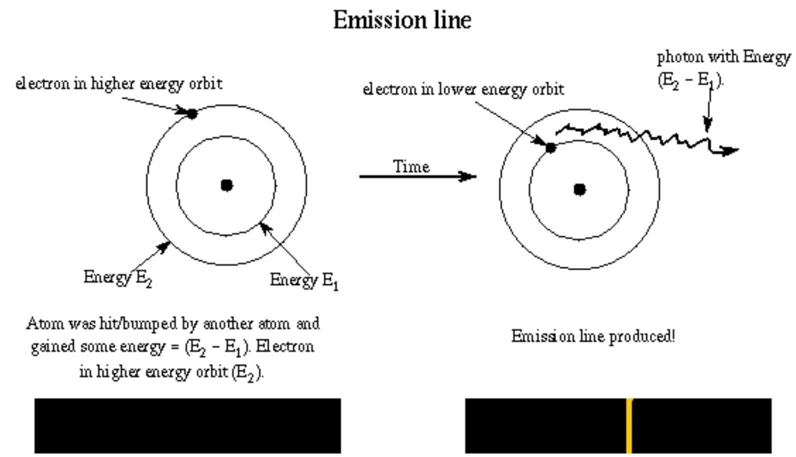
Adjusting the energy of each state in hydrogen by adding 13.6 eV (so that the ground state becomes zero), one gets a diagram where the energies of the transitions can be read off easily.

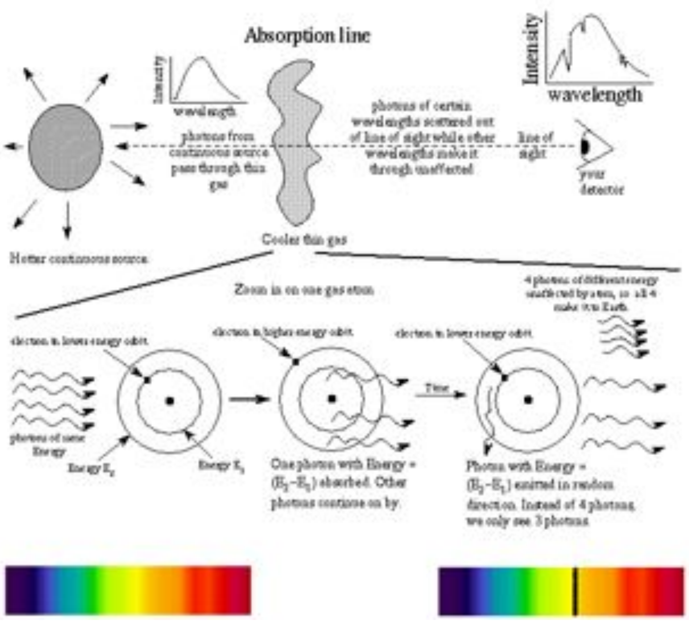
BALMER SERIES

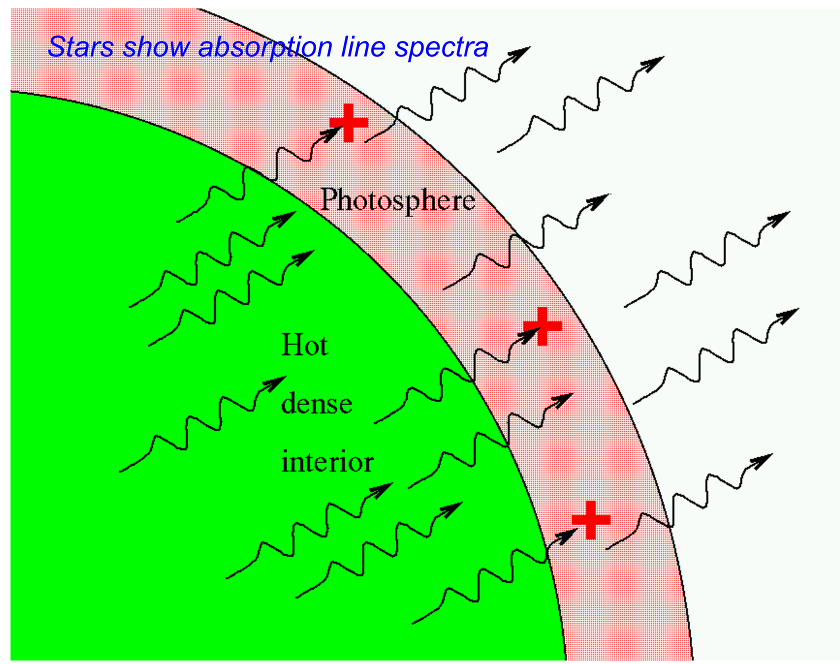


Hydrogen emission line spectrum
Balmer series


Heavier atoms have more energy
levels and more complex spectra
Hydrogen
Helium
Oxygen
Neon
Iron


Emission line
electron in higher energy orbit
electron in lower energy orbit
photon with Energy = (E_2 - E_1).
Time
Energy E_2
Energy E_1
Atom was hit/bumped by another atom and gained some energy = (E_2 - E_1). Electron in higher energy orbit (E_2).
Emission line produced!

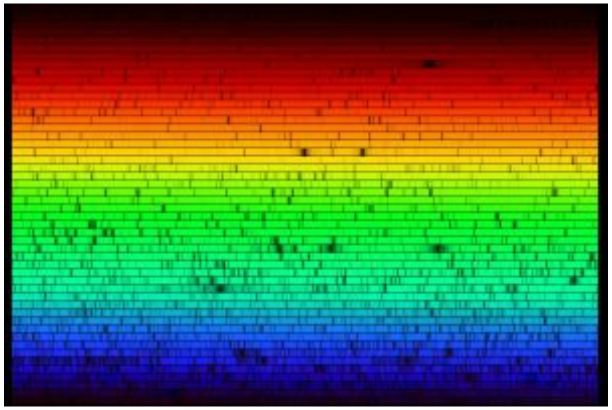

Absorption line
Intensity
wavelength
Cooler thin gas
Hotter continuous source
Zoom in on one gas atom
Time


Stars show absorption line spectra
Photosphere
Hot
dense
interior

Absorption Spectra:

provide majority of data for elemental abundances because:

- by far the largest number of elements can be observed
- low fractionation due to convection zone - still well mixed
- well understood - good models available



solar spectrum (Nigel Sharp, NOAO)

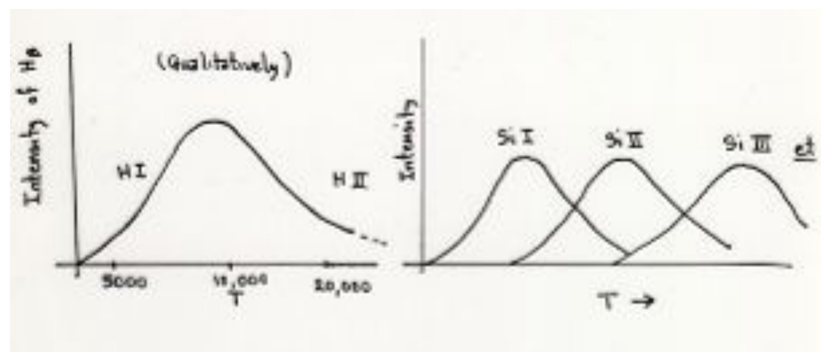
Notation: Ionization stages

H I	neutral hydrogen	1 p	1 e
H II	ionized hydrogen	1 p	0 e
He I	neutral helium	2 p	2 e
He II	singly ionized helium	2 p	1 e
He III	doubly ionized helium	2 p	0 e
C I	neutral carbon	6 p	6 e
C II	C^{+}	6 p	5 e
C III	C^{++}	6 p	4 e
etc.			

Ionization state of the absorbing gas

As the temperature in a gas is raised, electrons will be removed from atoms by collisions and interactions with light. The gas becomes *ionized*.

The degree of ionization depends on the atom considered and the density and temperature. High density favors recombination and high temperature favors ionization.

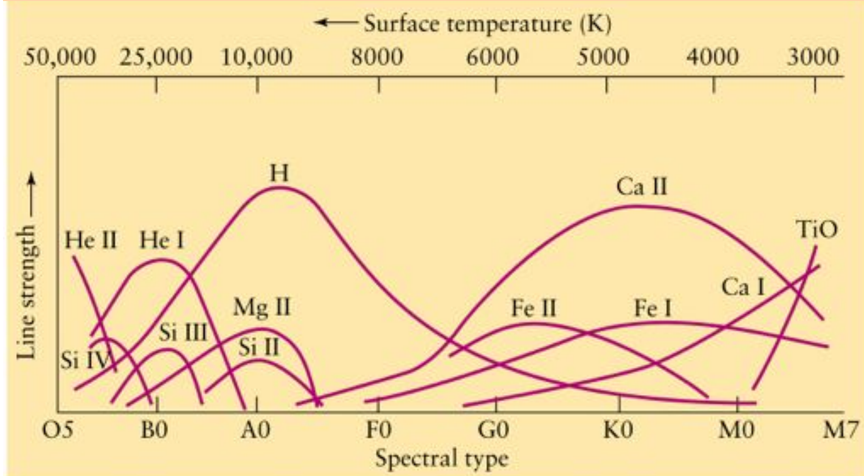


The ionization energy is the energy required to remove a single electron from a given ion. The excitation energy is the energy required to excite an electron from the ground state to the first excited state.

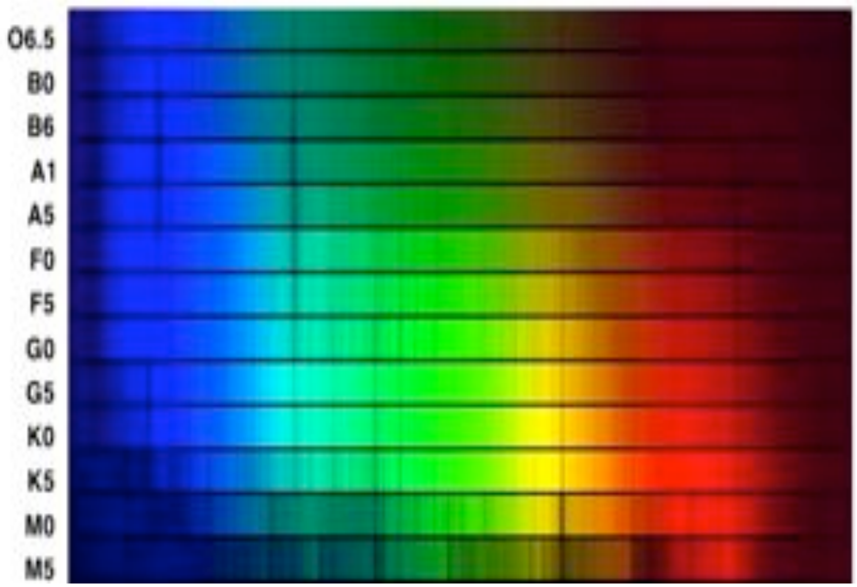
Ion	Excitation energy (eV)	Ionization energy (eV)
H I	10.2	13.6
He I	20.9	24.5
He II	40.8	54.4
rare Li I	1.8	5.4
Ne I	16.6	21.5
Na I	2.1	5.1
Mg I	2.7	7.6
Ca I	1.9	6.1

Li is He plus one proton, Na is Ne plus 1 proton, Ca is Ar plus 2 protons. The noble gases have closed electron shells and are very stable.

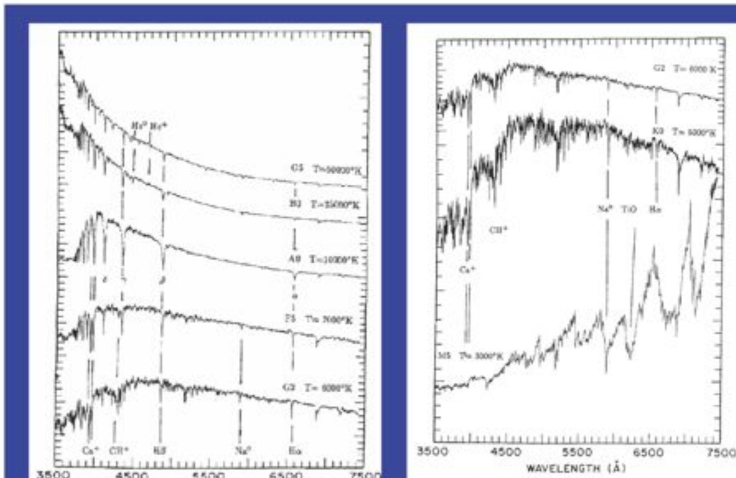
Some of the stronger lines in stars



The composition is not varying, just the temperature, and to a lesser extent, the density



and now L, T, and Y but these are mostly brown dwarfs



Spectra for O - G stars (left) and G - M stars (right)

Spectral Classes

Table 19-2 The Spectral Sequence

Spectral class	Color	Temperature (K)	Spectral lines	Examples
O	Blue-violet	30,000–50,000	Ionized atoms, especially helium	Naos (ζ Puppis), Mintaka (δ Orionis)
B	Blue-white	11,000–30,000	Neutral helium, some hydrogen	Spica (α Virginis), Rigel (β Orionis)
A	White	7500–11,000	Strong hydrogen, some ionized metals	Sirius (α Canis Majoris), Vega (α Lyrae)
F	Yellow-white	5900–7500	Hydrogen and ionized metals such as calcium and iron	Canopus (α Carinae), Procyon (α Canis Minoris)
G	Yellow	5200–5900	Both neutral and ionized metals, especially ionized calcium	Sun, Capella (α Aurigae)
K	Orange	3900–5200	Neutral metals	Arcturus (α Boötis), Aldebaran (α Tauri)
M	Red-orange	2500–3900	Strong titanium oxide and some neutral calcium	Antares (α Scorpii), Betelgeuse (α Orionis)
L	Red	1300–2500	Neutral potassium, rubidium, and cesium, and metal hydrides	Brown dwarf Teide 1
T	Red	below 1300	Strong neutral potassium and some water (H_2O)	Brown dwarf Gliese 229B

Main Sequence Luminosities and Lifetimes

Table 21-1 Main-Sequence Lifetimes

Mass ($M_\odot$)	Surface temperature (K)	Spectral class	Luminosity ($L_\odot$)	Main-sequence lifetime (10^6 years)
25	35,000	O	80,000	3
15	30,000	B	10,000	15
3	11,000	A	60	500
1.5	7000	F	5	3000
1.0	6000	G	1	10,000
0.75	5000	K	0.5	15,000
0.50	4000	M	0.03	200,000

DISTINGUISHING MAIN SEQUENCE STARS FROM RED GIANTS OF THE SAME COLOR

The surface gravity

$$g = \frac{GM}{R^2}$$

of a star is clearly larger for a smaller radius (if M is constant)

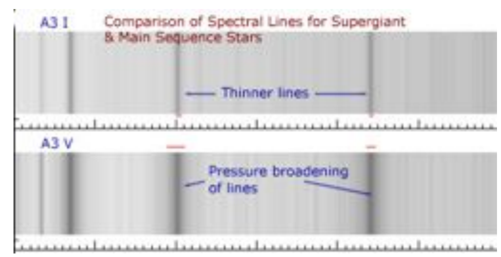
To support itself against this higher gravity, a the stellar photosphere must have a larger pressure. As we shall see later for an ideal gas

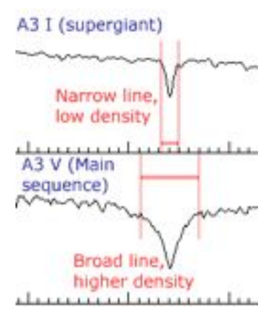
$$P = n\,k\,T$$

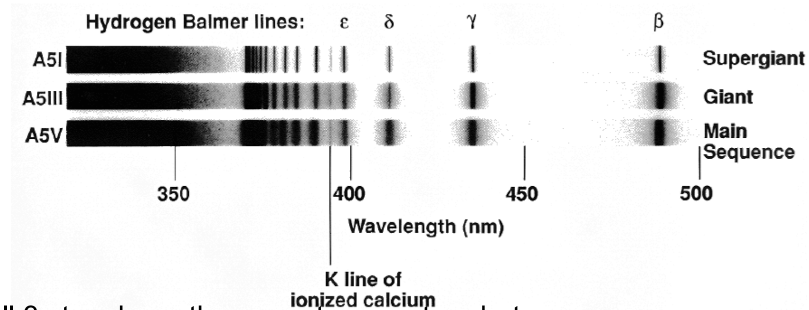
where n is the number density and T is the temperature. If two stars have the same temperature, T, the one with the higher pressure (smaller radius) will have the larger n, i.e., its atoms will be more closely crowded together. This has two effects:

1) At a greater density (and the same T) a gas is less ionized

2) If the density is high, the electrons in one atom “feel” the presence of other nearby nuclei. This makes their binding energy less certain. This spreading of the energy level is called “Stark broadening”







All 3 stars have the same temperature but,

- The supergiants have the narrowest absorption lines
- Small Main-Sequence stars have the broadest lines
- Giants are intermediate in line width and radius

- In 1943, Morgan & Keenan added the *Luminosity Class* as a second classification parameter:
  - Ia = Bright Supergiants
  - Ib = Supergiants
  - II = Bright Giants
  - III = Giants
  - IV = Subgiants
  - V = Main sequence

And so the sun is a G2-V star

ABUNDANCES AND IONIZATION

http://www.spms.ntu.edu.sg/PAP/courseware/statmech.pdf

The *Boltzman equation* derived from MB statistics describes excitation in a single atom

$$\boxed{\frac{n_s}{N} = \frac{g_s \exp(-\beta\varepsilon_s)}{\sum_r g_r \exp(-\beta\varepsilon_r)}} \qquad \beta = \frac{1}{kT}$$

from the Boltzmann equation one can also derive the *Saha equation* which describes ionization

http://www.phy.ohiou.edu/~mboett/astro401_fall12/saha.pdf

$$\boxed{\frac{N_{i+1}}{N_i} = \frac{g_{i+1}}{g_i}\frac{2}{n_e h^3}(2\pi m_e kT)^{3/2}\exp(-\chi/kT)}$$

where g_i and g_{i+1} are the partition functions for the two ionization states of the species i and i+1 and χ is the ionization potential of the species i (the difference in energy between states i and i+1). 2 is because the spins of the proton and electron can be alligned or counteralligned in the neutral atom

Aside:

$$V\Delta^3 p \sim h^3$$
$$1/V \sim n_e$$
$$\Delta p^3 \sim h^3 n_e$$

One often sees terms like $(2\pi m_e kT)$ and $1/(n_e h^3)$ when dealing with quantum statistics. As we will discuss a bit more next week, there exists a volume in momentum space, much like in real space - $4\pi p^2 dp$ (like $4\pi r^2 dr$ in spherical 3D coordinates). The ratio $8\pi p^2 dp / n_e h^3$ is essentially how many electrons one can have in that volume (between p and p +dp) according to the uncertainty principle (2 electrons per cell) in phase space times the volume of one electron V = $1/n_e$

In summing over all the states in a continuous distribution of momenta, one gets integrals like

$$\frac{8\pi}{n_e h^3}\int_0^\infty p^2 e^{-p^2/2mkT}\,dp = \frac{4\pi}{n_e h^3}(2m_e kT)^{3/2}\int_0^\infty \sqrt{x}\,e^{-x}dx$$

where $x = p^2/(2m_e kT)$. The integral is $\sqrt{\pi}/2$ so one gets $\dfrac{2(2\pi m_e kT)^{3/2}}{n_e h^3}$

As an example, lets apply these equations to understand the strength of Ca and H lines in the sun. In the spectrum the lines of Ca II (Ca^+) appear stronger than those of H. Is the sun made of calcium?

The calculation proceeds in 2 steps and follows GK 1.

We take as given the sun's photospheric temperature (5780 K) and *electron* pressure (this will be discussed more later) – 15 dyne $cm^{-2.}$ The latter will be used to provide the electron density, n_e, assuming ideal gas pressure $P_e = n_e kT$.

$$n_e = \frac{P_e}{kT} = \frac{15}{(1.38\times10^{-16})(5780)} = 1.9\times10^{13}\ \text{cm}^{-3}$$

First is hydrogen neutral or ionized?

$$\frac{n(H\,II)}{n(H\,I)} = \frac{g_{II}}{g_I}\frac{2}{n_e h^3}\left(2\pi m_e kT\right)^{3/2}\exp(-\chi/kT)$$

g_{II} is just the statistical weight of the proton - 1 if it is unbound

g_I is the partiction function for the neutral H atom which in the general case is a bit complicated because one must assign statistical weights to all the bound states. From QM each energy state n is $2n^2$ degenerate (i.e., there are n^2 levels with different m and l having the same energy. Further the binding energy of each state is 13.6 eV $(1-\frac{1}{n^2})$ so

$$g_I = \sum_{n=1}^{\infty} g_n e^{-(E_i-E_1)/kT} = \sum_{n=1}^{\infty} 2n^2 \exp\left(\frac{-13.6\,eV}{kT}\left(1-\frac{1}{n^2}\right)\right)$$

but since kT $=8.622\times10^{-5}(5780\text{ K}) = 0.50\ eV$, all terms are negligible except n = 1, the ground state for which $g_I = 2$. The electron and the proton spins may be alligned or counter-alligned

$$\frac{n(\text{H II})}{n(\text{H I})} = \frac{1}{2}\,\frac{2}{1.9\times10^{13}}\left(\frac{2\pi m_e kT}{h^2}\right)^{3/2} e^{-13.6/0.50}$$

$$\left(\frac{2\pi m_e kT}{h^2}\right)^{3/2} = 2.41\times10^{15}\,T(K)^{3/2}$$

$$\frac{n(\text{H II})}{n(\text{H I})} = 8\times10^{-5}$$

The hydrogen is neutral to a high degree. Note that this also implies that the number of free electrons is very much less than that of the ions and electronic pressure, in the solar photosphere is a small fraction of the total pressure.

What about the number of H in the n = 2 level that can absorb Balmer alpha?
The difference in the n = 1 and 2 energy levels is 13.6 eV times $(1 - \frac{1}{4}) = 10.2$ eV. The population factor is then given by the Boltzmann distribution

$$\frac{N_{n=2}}{N_{n=1}} = \frac{g_2}{g_I}\exp(-10.2/kT) = \frac{2(2^2)}{2}e^{-10.2/0.50}$$
$$= 5.5\times10^{-9}$$

a) Less than one hundred millionth of the H atoms are in their first excited state (many fewer in higher states)

b) The number rises rapidly with increasing temperature so (Balmer) hydrogen lines should be stronger in stars more massive than the sun - for awhile.

What about Ca? Experimentally GK say the partition function for neutral Ca between 5000 and 6000 K is 1.32 and for Ca II is 2.30. The ratio of singly ionized Ca to neutral Ca is then

$$\frac{n(Ca\ II)}{n(Ca\ I)} = \frac{2g(Ca\ II)}{g(Ca\ I)n_e}\left(\frac{2\pi m_e kT}{h^2}\right)^{3/2} \exp(-6.11\,eV / kT)$$

$$= \frac{2(2.3)}{1.32(1.9\times10^{13})} 2.41\times10^{15}(5780)^{3/2}\ e^{-6.11/0.50}$$

$$= 950$$

Unlike H, Ca is overwhelmingly ionized. We could also calculate the ratio of Ca III/Ca II but it is small.

The fraction of Ca that is in the ground state is the partition function for the ground state, which, it turns out, is 2, divided by the total partition function for Ca II which is 2.3, so 87% is in the ground state.

Together these results imply that:

a) Hydrogen is neutral but only 5×10^{-9} is in the first excited state and capable of absorbing a Balmer alpha photon

b) Most calcium is Ca II in its ground state

If the observed line strengths show 400 more Ca II absorbers than H_α absorbers, the actual abundance ratio of Ca to H is

$$\frac{N(Ca)}{N(H)} = 400\left(\frac{5.5\times10^{-9}}{0.87}\right) = 2.5\times10^{-6}$$

As we shall see the actual modern abundance ratio is 2.1×10^{-6}

Oscilator strengths?

For the same electron pressure, at what temperature will hydrogen be half ionized?

$$\frac{N_{i+1}}{N_i} = 1 = \frac{g_{i+1}}{g_i}\frac{2}{n_e h^3}(2\pi m_e kT)^{3/2} \exp(-\chi / kT)$$

$$= \frac{g_{i+1}}{g_i}\frac{2}{P_e}\left(\frac{2\pi m_e}{h^2}\right)^{3/2} (kT)^{5/2} \exp(-\chi / kT)$$

$$\left(\frac{2\pi m_e}{h^2}\right)^{3/2} = 1.49\times10^{39} \qquad \chi = 13.6\,eV$$

kT in erg $= 1.602\times10^{-12}\,kT$ in eV

$(kT)^{5/2}$ in erg $= 3.25\times10^{-30}\,(kT)^{5/2}$ in eV

IF P_e = constant = 15 dyne cm^{-2}

incorrect

$$1 = \left(1.49\times10^{39}\right)\left(3.25\times10^{-30}\right)\frac{(kT)_{eV}^{5/2}}{15}\, e^{-13.6/kT_{ev}}$$

$$x^{5/2}e^{-13.6/x} = 3.10\times10^{-9} \qquad x = 0.724\ \text{eV}\quad or\ T = 8400\ \text{K}$$

But this underestimates T considerably because P_e will increase with temperature due to ionization. Note that bigger P_e (or n_e) means less ionization

Done correctly, ´when H becomes mostly ionized.

n_e = n(HII).

$$\frac{n^2(H\ II)}{n(H\ I)} = \frac{2g_{II}}{g_I}\left(\frac{2\pi m_e kT}{h^2}\right)^{3/2} e^{-13.6/kT}$$

$$n(H\,I) + n(H\,II) = n(H) = \rho X_H N_A \qquad \text{Let } n(H\ II) = y\ n(H)$$

$$n(H\ I) = (1-y)n(H) \qquad X_H = 0.7$$

Then

$$\frac{y^2 n(H)}{(1-y)} = \left(\frac{2\pi m_e kT}{h^2}\right)^{3/2} e^{-13.6/kT}$$

$$\frac{y^2}{(1-y)} = \frac{1}{\rho N_A X_H}\left(\frac{2\pi m_e kT}{h^2}\right)^{3/2} e^{-13.6/kT} \qquad P_{gas} = \frac{\rho N_A kT}{\mu}$$

$$= \frac{1}{\mu P_{gas}}\left(\frac{2\pi m_e kT}{h^2}\right)^{3/2} (kT)e^{-13.6/kT}$$

The left hand side is 1/2 if y = 1/2, so we have pretty much the same equation we had before except with μP_{gas} ($\mu \approx 0.6$) instead of P_e

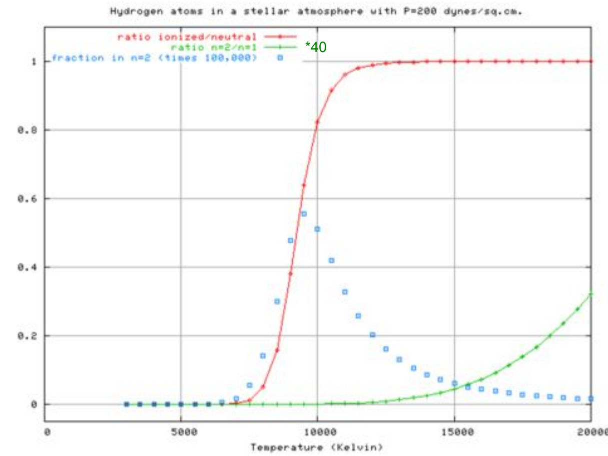
$$\frac{1}{2} = \frac{1}{\mu P_{gas}}\left(\frac{2\pi m_e kT}{h^2}\right)^{3/2}(kT)\, e^{-13.6/kT}$$

As we shall show next time the pressure in the solar photosphere times μ is a few $\times 10^4$ and this declines as "g" in heavier stars. Solving as before (and including the .7 for H abundance and the 33% contribution of electron pressure)

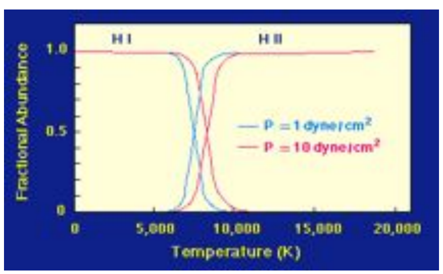
$$x^{5/2} e^{-13.6/x} \approx 2\times 10^{-6}$$
$$T \approx 12{,}000\ K$$

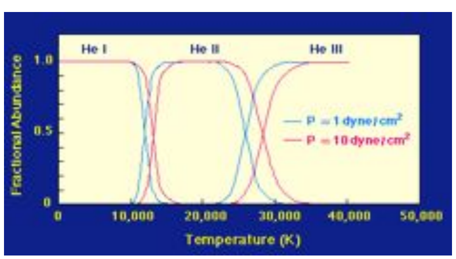
and this is closer to correct, though not very different because of the exponential. Actually P_{gas} declines at higher masses so this is an overestimate.

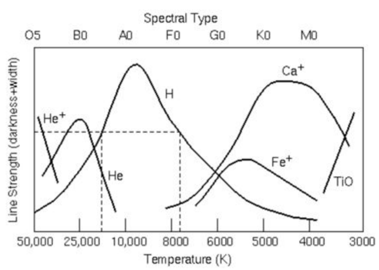
http://spiff.rit.edu/classes/phys440/lectures/saha/saha.html



http://csep10.phys.utk.edu/astr162/lect/stars/spectra.html



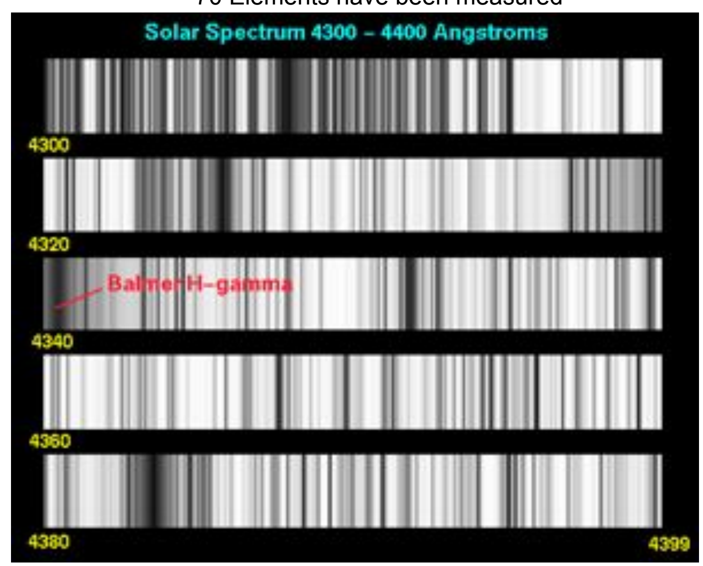




(Part of) the solar spectrum

Over 100,000 lines are visible in the entire spectrum

70 Elements have been measured



In practice, to obtain abundances, one builds a model "stellar atmosphere" in which heat flux, gravity, and hydrostatic equilibrium (TBD) are given and solves consistently for the ionization, electron density, pressure, and line strengths.

One of many concerns is the assumption of "local thermodynamic equilibrium", that the level populations are accurately represented by the Boltzmann equation.

In non-LTE situations one must solve rate equations to get the level populations.

Complications for photospheric abundance determinations

- **Oscillator strengths**:

  Need to be measured in the laboratory - still not done with sufficient accuracy for a number of elements.

- **Line width**

  Depends on atomic properties but also thermal and turbulent broadening. Need an atmospheric model.

- **Line blending**

- **Ionization State**

- **Model for the solar atmosphere**

  Turbulent convection. Possible non-LTE effects.
  3D models differ from 1 D models. See Asplund, Grevesse, and Sauval (2007).

Meteorites

H. Schatz

Meteorites can provide accurate information on elemental abundances in the presolar nebula. More precise than solar spectra data in some cases. Principal source for isotopic information.

But some gases escape and cannot be determined this way (for example hydrogen and noble gases)

Not all meteorites are suitable - most of them are fractionated and do not provide representative solar abundance information. Chondrites are meteorites that show little evidence for melting and differentiation.

Classification of meteorites:

Group	*Subgroup*	*Frequency*
Stones	Chondrites	86%
	Achondrites	7%
Stony Irons		1.5%
Irons		5.5%

Carbonaceous chondrites are 4.6% of meteor falls.

H Schatz

Use **carbonaceous chondrites** (~5% of falls)

Chondrites: Have Chondrules - small ~1mm size shperical inclusions in matrix
believed to have formed very early in the presolar nebula
accreted together and remained largely unchanged since then

Carbonaceous Chondrites have lots of organic compounds that indicate
very little heating (some were never heated above 50 degrees K)

http://www.psrd.hawaii.edu/May06/meteoriteOrganics.html

"Some carbonaceous chondrites smell. They contain volatile compounds that slowly give off chemicals with a distinctive organic aroma. Most types of carbonaceous chondrites (and there are lots of types) contain about 2% organic compounds, and these are very important for understanding how organic compounds might have formed in the solar system. They even contain complex compounds such as amino acids, the building blocks of proteins."

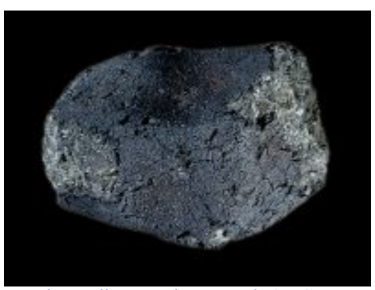
There are various subclasses of carbonaceous chondrites. The C-I' s and C-M's are general thought to be the most primitive because they contain water and organic material. They are fine grained and contain no chondrules or refractory inclusions.

The CM meteorite Murchison, has over 70 extraterrestrial amino acids and other compounds including carboxylic acids, hydroxy carboxylic acids, sulphonic and phosphoric acids, aliphatic, aromatic, and polar hydrocarbons, fullerenes, heterocycles, carbonyl compounds, alcohols, amines, and amides.

Five CI chondrites have been observed to fall: Ivuna, Orgueil, Alais, Tonk, and Revelstoke. Several others have been found by Japanese expeditions in Antarctica. They are very fragile and subject to weathering. They do not survive long on the earth's surface after they fall.

The table on the following page summarizes (Lodders et al (2009) view of) the current elemental abundances and their uncertainties in the sun and in meteorites.

The Orgueil meteorite is especially popular for abundance analyses. It is a very primitive (and rare) carbonaceous chondrite that fell in France in 1864. Over 13 kg of material was recovered.



http://www.meteoritestudies.com/protected_ORGUEIL.HTM

Katharina Lodders, Astrophysical Journal, 591, 1220 (2003) and 2009 update (will be posted)

Uncertain elements above CNO.

Indium, tungsten, to a lesser extent Tl, Au, Cl, Rb, Hf

Unseen in the sun

Arsenic, selenium, bromine, technetium (unstable), iodine, cesium, tantalum, rhenium, mercury, bismuth, promethium (unstable)

Table 4. Elemental abundances in the solar photosphere and in CI-chondrites
[log N(H) = A(H) = 12]

		Solar Photosphere	σ dex	Orgueil CI-chondrite	σ dex	Sun/Meteorite N_{sun}/N_{met}
1	H	12		8.24	0.04	5710
2	He	10.925	0.02	1.31		4.1E+09
3	Li	1.10	0.10	3.28	0.05	0.01
4	Be	1.38	0.09	1.32	0.03	1.15
5	B	2.70	0.17	2.81	0.04	0.78
6	C	8.39	0.04	7.41	0.04	9.46
7	N	7.86	0.12	6.28	0.06	38.4
8	O	8.73	0.07	8.42	0.04	2.06
9	F	4.56	0.30	4.44	0.06	1.32
10	Ne	8.05	0.10	-1.10		1.4E+09
11	Na	6.30	0.03	6.29	0.02	*1.03*
12	Mg	7.54	0.06	7.55	0.01	*0.98*
13	Al	6.47	0.07	6.45	0.01	*1.05*
14	Si	7.52	0.06	7.53	0.01	*0.97*
15	P	5.46	0.04	5.45	0.04	*1.03*
16	S	7.14	0.01	7.17	0.02	*0.92*
17	Cl	5.50	0.30	5.25	0.06	1.79
18	Ar	6.50	0.10	-0.48		9.6E+06
19	K	5.12	0.03	5.10	0.02	*1.06*
20	Ca	6.33	0.07	6.31	0.02	*1.04*
21	Sc	3.10	0.10	3.07	0.02	1.07
22	Ti	4.90	0.06	4.93	0.03	*0.94*
23	V	4.00	0.02	3.98	0.02	*1.05*
24	Cr	5.64	0.01	5.66	0.01	*0.96*
25	Mn	5.37	0.05	5.50	0.01	*0.75*
26	Fe	7.45	0.08	7.47	0.01	*0.95*
27	Co	4.92	0.08	4.89	0.01	*1.08*
28	Ni	6.23	0.04	6.22	0.01	*1.03*
29	Cu	4.21	0.04	4.27	0.04	*0.88*
30	Zn	4.62	0.15	4.65	0.04	0.94
31	Ga	2.88	0.10	3.10	0.02	0.61
32	Ge	3.58	0.05	3.60	0.04	*0.95*
33	As			2.32	0.04	
34	Se			3.36	0.03	
35	Br			2.56	0.06	
36	Kr	3.28	0.08	-2.25		3.4E+05
37	Rb	2.60	0.10	2.38	0.03	1.64
38	Sr	2.92	0.05	2.90	0.03	*1.04*
39	Y	2.21	0.02	2.19	0.04	*1.05*
40	Zr	2.58	0.02	2.55	0.04	*1.07*
41	Nb	1.42	0.06	1.43	0.04	*0.98*

Table 4. Elemental abundances in the solar photosphere and in CI-chondrites
[log N(H) = A(H) = 12]

		Solar Photosphere	σ dex	Orgueil CI-chondrite	σ dex	Sun/Meteorite N_{sun}/N_{met}
42	Mo	1.92	0.05	1.96	0.04	*0.92*
44	Ru	1.84	0.07	1.78	0.03	*1.14*
45	Rh	1.12	0.12	1.08	0.04	1.09
46	Pd	1.66	0.04	1.67	0.02	*0.97*
47	Ag	0.94	0.30	1.22	0.02	0.52
48	Cd	1.77	0.11	1.73	0.03	1.10
49	In	<1.50	UL	0.78	0.03	5.21
50	Sn	2.00	0.30	2.09	0.06	0.81
51	Sb	1.00	0.30	1.03	0.06	0.94
52	Te			2.20	0.03	
53	I			1.57	0.08	
54	Xe	2.27	0.08	-1.93		1.6E+04
55	Cs			1.10	0.02	
56	Ba	2.17	0.07	2.20	0.03	*0.94*
57	La	1.14	0.03	1.19	0.02	*0.88*
58	Ce	1.61	0.06	1.60	0.02	*1.02*
59	Pr	0.76	0.04	0.78	0.03	*0.96*
60	Nd	1.45	0.05	1.47	0.02	*0.96*
62	Sm	1.00	0.05	0.96	0.02	*1.10*
63	Eu	0.52	0.04	0.53	0.02	*0.97*
64	Gd	1.11	0.05	1.07	0.02	*1.10*
65	Tb	0.28	0.10	0.34	0.03	0.88
66	Dy	1.13	0.06	1.15	0.02	*0.96*
67	Ho	0.51	0.10	0.49	0.03	1.04
68	Er	0.96	0.06	0.94	0.02	*1.04*
69	Tm	0.14	0.04	0.14	0.03	*1.00*
70	Yb	0.86	0.10	0.94	0.02	0.83
71	Lu	0.12	0.08	0.11	0.02	*1.02*
72	Hf	0.88	0.08	0.73	0.02	*1.43*
73	Ta			-0.14	0.04	
74	W	1.11	0.15	0.67	0.04	2.75
75	Re			0.28	0.04	
76	Os	1.45	0.11	1.37	0.03	1.21
77	Ir	1.38	0.05	1.34	0.02	*1.10*
78	Pt	1.74	0.30	1.64	0.03	
79	Au	1.01	0.18	0.82	0.04	1.54
80	Hg			1.19	0.08	
81	Tl	0.95	0.20	0.79	0.03	1.43
82	Pb	2.00	0.06	2.06	0.03	*0.88*
83	Bi			0.67	0.04	
90	Th	< 0.08	UL	0.08	0.03	1.01
92	U	< -0.47	UL	-0.52	0.03	1.11

σ – standard deviation in dex: $(10^{(\sigma \text{ in dex})} - 1) \times 100 = \sigma$ in %;
meteorite data: log N_{El} + 1.533 where N_{El} = abundance relative to 10^6 Si atoms (Table 1);
UL – upper limit;
Last column: Values in italics indicate the 39 elements used for calculating conversion factor.

Scanning the table one notes:

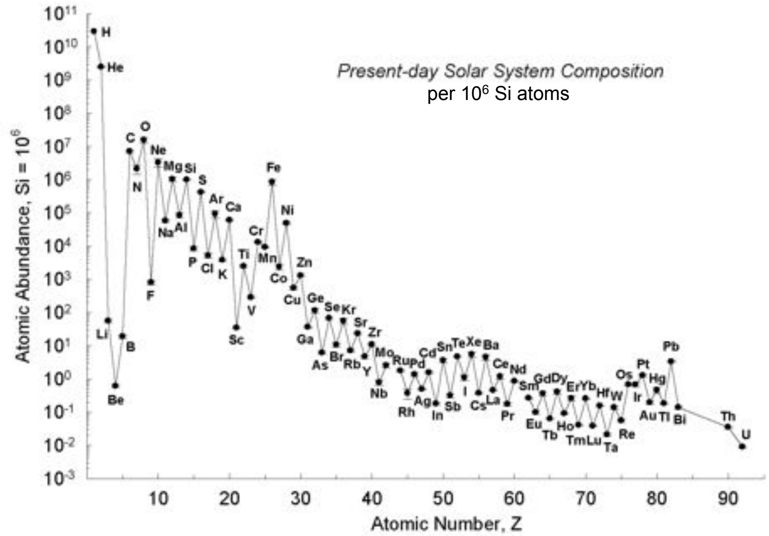
a) H and H have escaped from the meteorites

b) Li is depleted in the sun, presumably by nuclear reactions in the convection zone

c) CNO also seem to be depleted in the meteorites

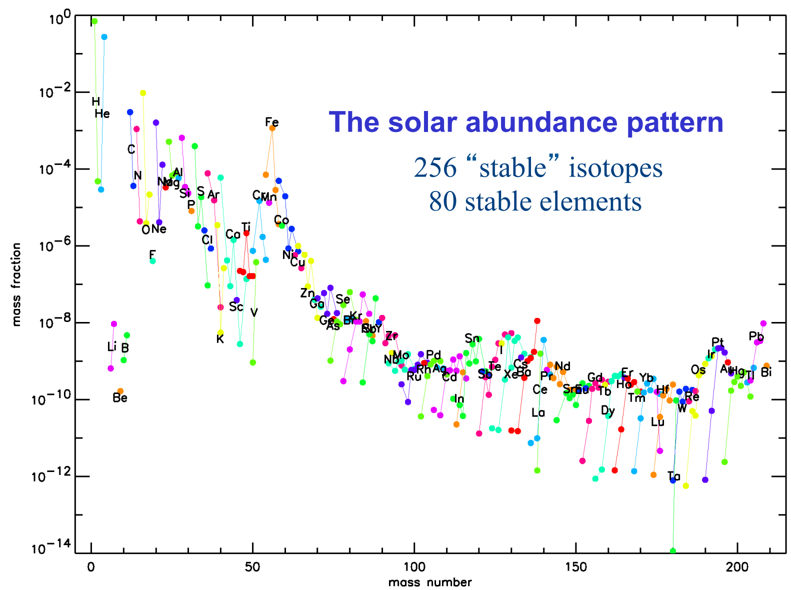
d) The noble gases have been lost, Ne, Ar, etc

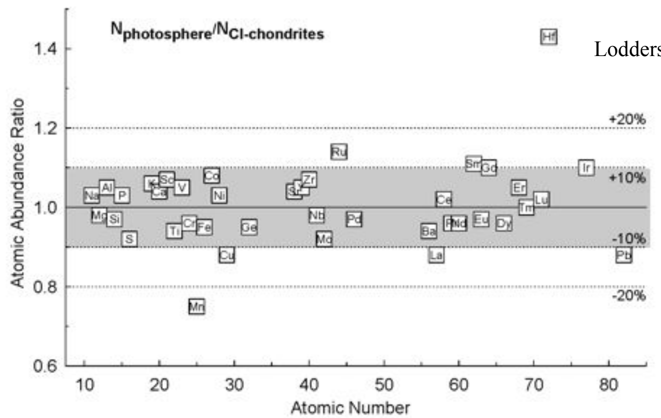
e) Agreement is pretty good for the rest – where the element has been measured in both the sun and meteorites



Lodders (2009) translated into mass fractions

h1	7.11E-01	si28	7.02E-04	ti47	2.34E-07	zn66	6.48E-07
h2	2.75E-05	si29	3.69E-05	ti48	2.37E-06	zn67	9.67E-08
he3	3.42E-05	si30	2.51E-05	ti49	1.78E-07	zn68	4.49E-07
he4	2.73E-01	p31	6.99E-06	ti50	1.74E-07	zn70	1.52E-08
li6	6.90E-10	s32	3.48E-04	v50	9.71E-10	ga69	4.12E-08
li7	9.80E-09	s33	2.83E-06	v51	3.95E-07	ga71	2.81E-08
be9	1.49E-10	s34	1.64E-05	cr50	7.72E-07	ge70	4.63E-08
b10	1.01E-09	s36	7.00E-08	cr52	1.54E-05	ge72	6.20E-08
b11	4.51E-09	cl35	3.72E-06	cr53	1.79E-06	ge73	1.75E-08
c12	2.32E-03	cl37	1.25E-06	cr54	4.54E-07	ge74	8.28E-08
c13	2.82E-05	ar36	7.67E-05	mn55	1.37E-05	ge76	1.76E-08
n14	8.05E-04	ar38	1.47E-05	fe54	7.27E-05	as75	1.24E-08
n15	3.17E-06	ar40	2.42E-08	fe56	1.18E-03	se74	1.20E-09
o16	6.83E-03	k39	3.71E-06	fe57	2.78E-05	se76	1.30E-08
o17	2.70E-06	k40	5.99E-09	fe58	3.76E-06	se77	1.07E-08
o18	1.54E-05	k41	2.81E-07	co59	3.76E-06	se78	3.40E-08
f19	4.15E-07	ca40	6.36E-05	ni58	5.26E-05	se80	7.27E-08
ne20	1.66E-03	ca42	4.45E-07	ni60	2.09E-05	se82	1.31E-08
ne21	4.18E-06	ca43	9.52E-08	ni61	9.26E-07	br79	1.16E-08
ne22	1.34E-04	ca44	1.50E-06	ni62	3.00E-06	br81	1.16E-08
na23	3.61E-05	ca46	3.01E-09	ni64	7.89E-07	Etc.	
mg24	5.28E-04	ca48	1.47E-07	cu63	6.40E-07		
mg25	6.97E-05	sc45	4.21E-08	cu65	2.94E-07		
mg26	7.97E-05	ti46	2.55E-07	zn64	1.09E-06.		





Lodders et al (2009)

Off scale In, W, Tl, Au, Cl, Rb

Abundances outside the solar neighborhood ?

H. Schatz

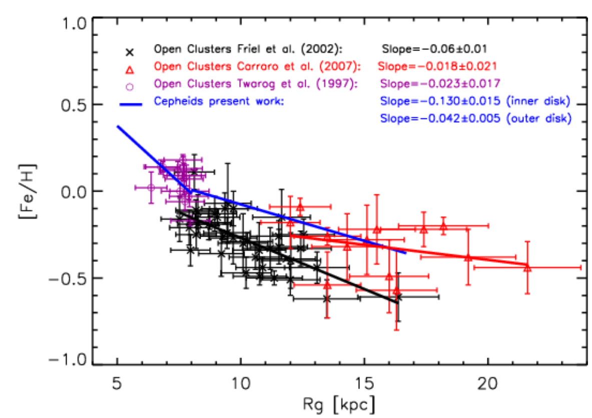
Abundances outside the solar system can be determined through:

- Stellar absorption spectra of other stars than the sun
- Interstellar absorption spectra
- Emission lines, H II regions
- Emission lines from Nebulae (Supernova remnants, Planetary nebulae, …)
- γ-ray detection from the decay of radioactive nuclei
- Cosmic Rays
- Presolar grains in meteorites

Table 11. Average abundances (A) of main sequence F and G stars with close to solar metallicity ($|\Delta[Fe/H]|<0.05$) and of young stars (age ~1 Ga) from the solar neighborhood, of main sequence B stars from a ±2 kpc wide ring around the solar circle, and abundances of the Orion nebula

	Present-day solar system	Nearby F & G stars solar metallicity			Nearby F & G stars age < 1 Ga			B dwarfs			Orion nebula		
El.	*this work*	A	σ_{abd}	σ_*	A	σ_*	*ref.*	A	σ_*	*ref.*	A	σ_{abd}	*ref.*
He	10.93							11.02	0.05	3	10.99	0.01	10
C	8.39	8.37	0.06	0.11	8.39	0.11	2	8.32	0.10	4	8.52	0.05	10
N	7.86							7.73	0.28	5	7.73	0.09	10
O	8.73	8.75		0.07	8.77	0.13	1	8.63	0.18	4	8.73	0.09	10
Ne	8.05							7.97	0.07	6	8.05	0.07	10
Na	6.29	6.30	0.03	0.16	6.27	0.10	1						
Mg	7.54	7.63	0.06	0.32	7.64	0.21	1	7.59	0.15	7			
Al	6.46	6.52	0.05	0.24	6.54	0.22	1	6.24	0.14	5			
Si	7.53	7.60	0.05	0.28	7.61	0.23	1	7.50	0.21	5			
S	7.16	7.17	0.16		7.29	0.10		7.22	0.10	4	7.22	0.04	10
Ar	6.50							6.63	0.06	8	6.62	0.05	10
Ca	6.31	6.42	0.03	0.37	6.48	0.39	1						
Ti	4.93	4.92	0.03	0.11	4.94	0.14	1						
Cr	5.65	5.66	0.02	0.13	5.73	0.28	1						
Fe	7.46	7.55	0.06	0.12	7.61	0.25	1	7.46	0.08	9			
Ni	6.22	6.22	0.02	0.09	6.25	0.07	1						
Zn	4.65	4.53	0.06	0.27	4.54	0.13	1						
Z	0.0141	0.0141			0.0148			0.0119					

σ_{abd} - accuracy of the individual abundance determinations from stellar spectra, σ_* - scattering of the stellar abundances of the corresponding group of stars around the mean; Z - metallicity estimated from these abundances.
Sun: Tables 6,7.
Data sources: (1)[05B3], (2)[06B], (3)[04L2], (4)[04D], (5)[00R], (6)[08M2], (7)[05L2], (8)[08L4], (9)[94C2], (10)[04E]



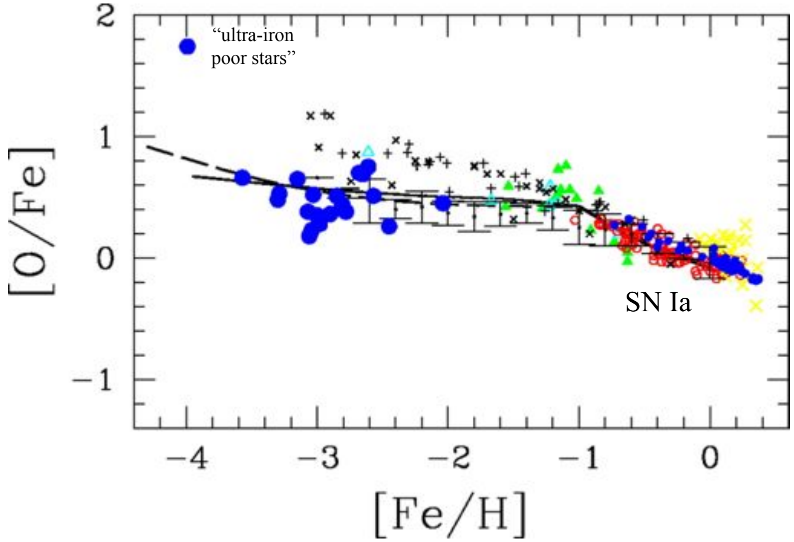
but see also Najarro et al (ApJ, 691, 1816 (2009)) who find solar iron near the Galactic center.

From Pedicelli et al. (A&A, 504, 81, (2009)) studied abundances in Cepheid variables. Tabulated data from others for open clusters.

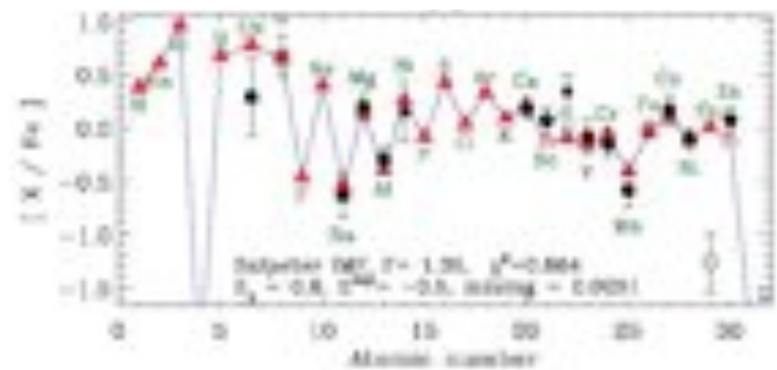
For entire region 5 – 17 kpc, Fe gradient is -0.051+- 0.004 dex/kpc but it is ~3 times steeper in the inner galaxy. Spans a factor of 3 in Fe abundance.

Variation with metallicity

Kobayashi et al, *ApJ*, **653**, 1145, (2006)



Integrated yield of 126 masses 11 - 100 $M_\odot$ (1200 SN models), with Z= 0, Heger and Woosley (2008, ApJ 2010) compared with low Z observations by Lai et al (*ApJ*, 681, 1524, (2008)). Odd-even effect due to sensitivity of neutron excess to metallicity and secondary nature of the s-process.



28 metal poor stars in the Milky Way Galaxy
$-4 < [Fe/H] < -2$; 13 are $< -.26$