I. Abundances – The Composition of the Universe

Before answering the question of the origin of the elements we want to see what elements are actually there - in other words

What is the Universe made of ? Answer: We have no clue ….

74% Dark Energy (don't know what it is)
22% Cold dark matter (don't know what it is)
4% Nuclei and electrons (visible as stars ~0.5%) ⟵ **Topic of this course**

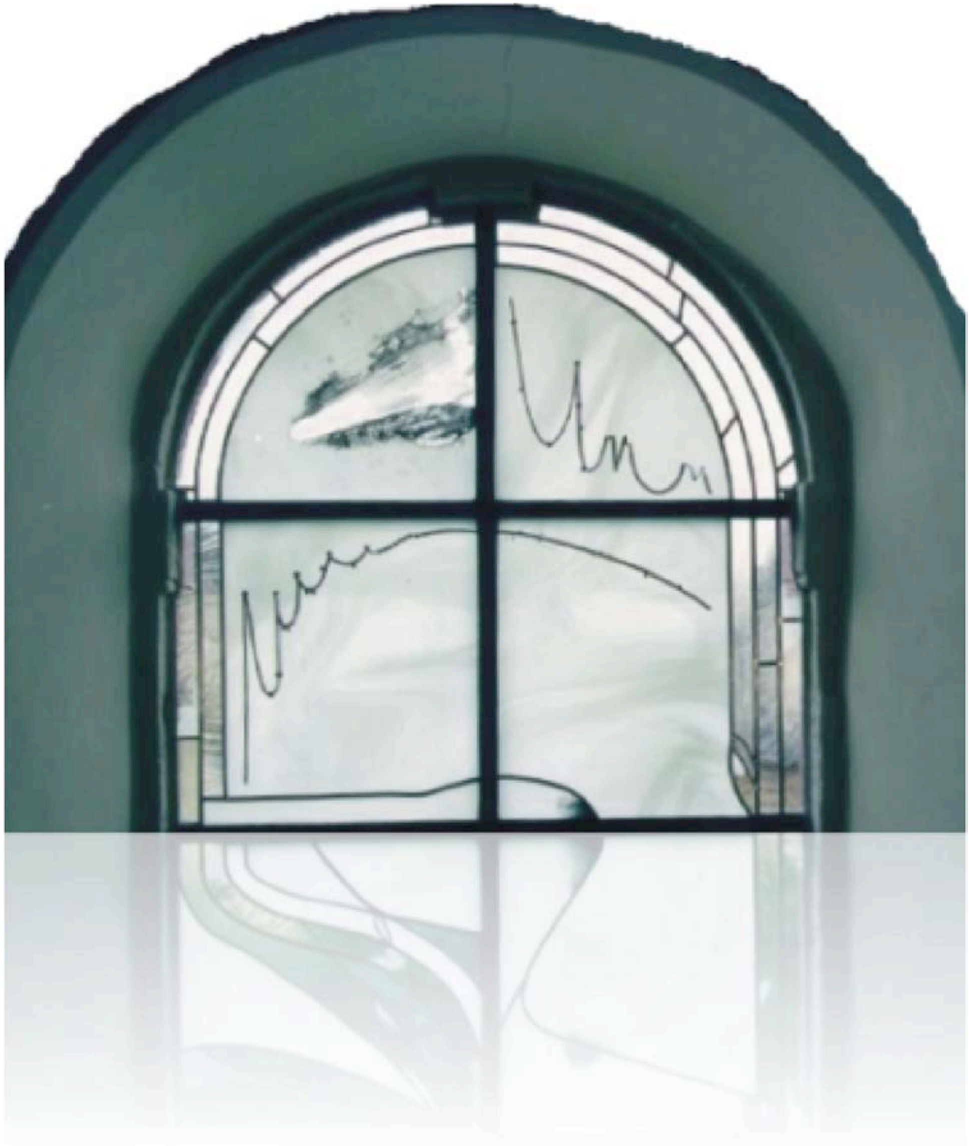
Why bother with 4% ???

Important things are made of it:

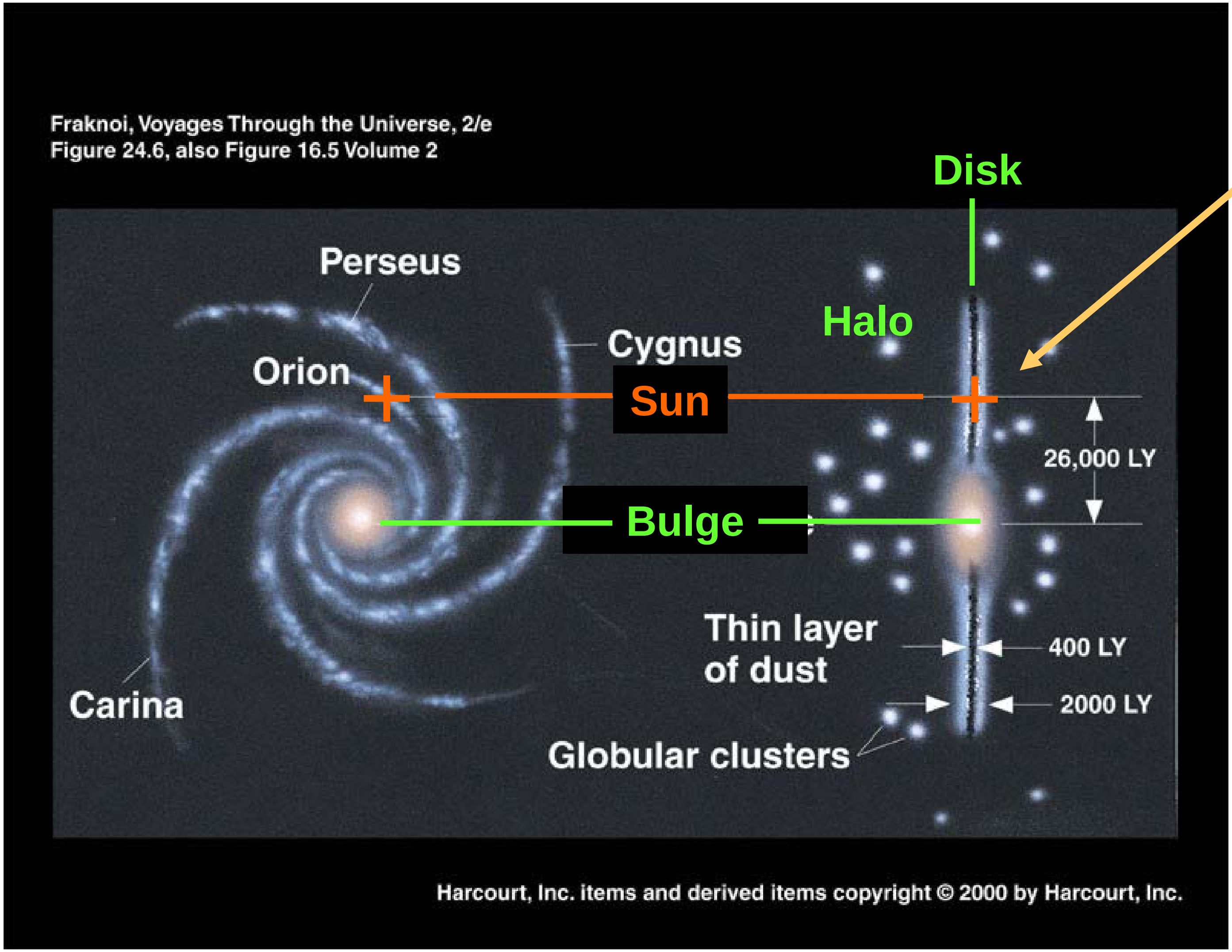
<u>Questions to be answered:</u>

- What kind of nuclei (nuclides) is the universe made of ?
- How abundant is each element ? Each nuclide ?

Window of the protestant church in Wixhausen, Germany



The solar abundance distribution



solar abundances:

Elemental (and isotopic) composition of Galaxy at location of solar system at the time of it's formation

How can solar abundances be determined ?

1. Earth material

Problem: chemical fractionation modified the local composition strongly compared to pre solar nebula and overall solar system.

for example: Quarz is 1/3 Si and 2/3 Oxygen and not much else. This is not the composition of the solar system.

But: Isotopic compositions mostly unaffected (as chemistry is determined by number of electrons (protons), not the number of neutrons).

$\longrightarrow$ **main source for isotopic composition of elements**

2. Solar spectra

Sun formed directly from presolar nebula - (largely) unmodified outer layers create spectral features

3. Unfractionated meteorites

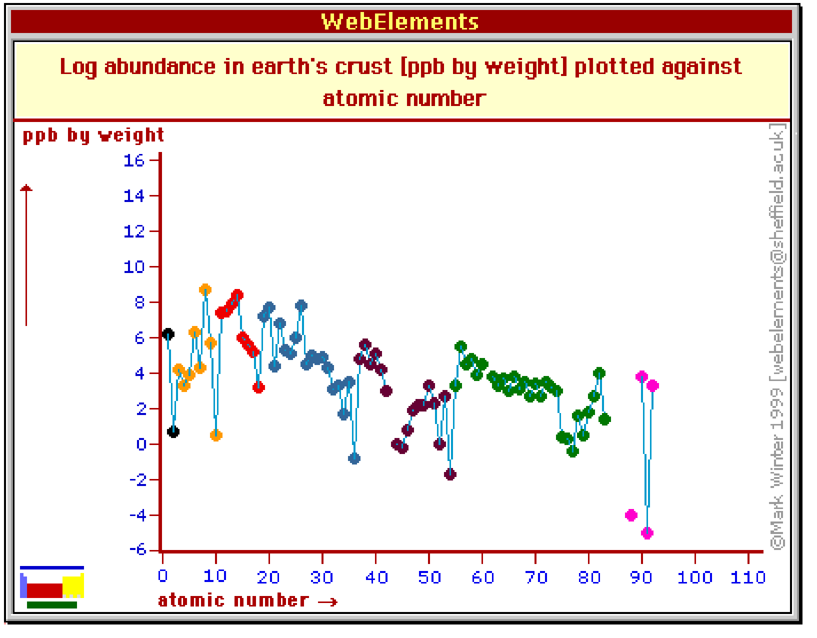
Certain classes of meteorites formed from material that never experienced high pressure or temperatures and therefore was never fractionated. These meteorites directly sample the presolar nebula

History:

1889, Frank Wigglesworth Clarke read a paper before the Philosophical Society of Washington "The Relative Abundance of the Chemical Elements"

"An attempt was made in the course of this investigation to represent the relative abundances of the elements by a curve, taking their atomic weight for one set of the ordinates. It was hoped that some sort of periodicity might be evident, but no such regularity appeared"

Current "abundance" distribution of elements in the earths crust:



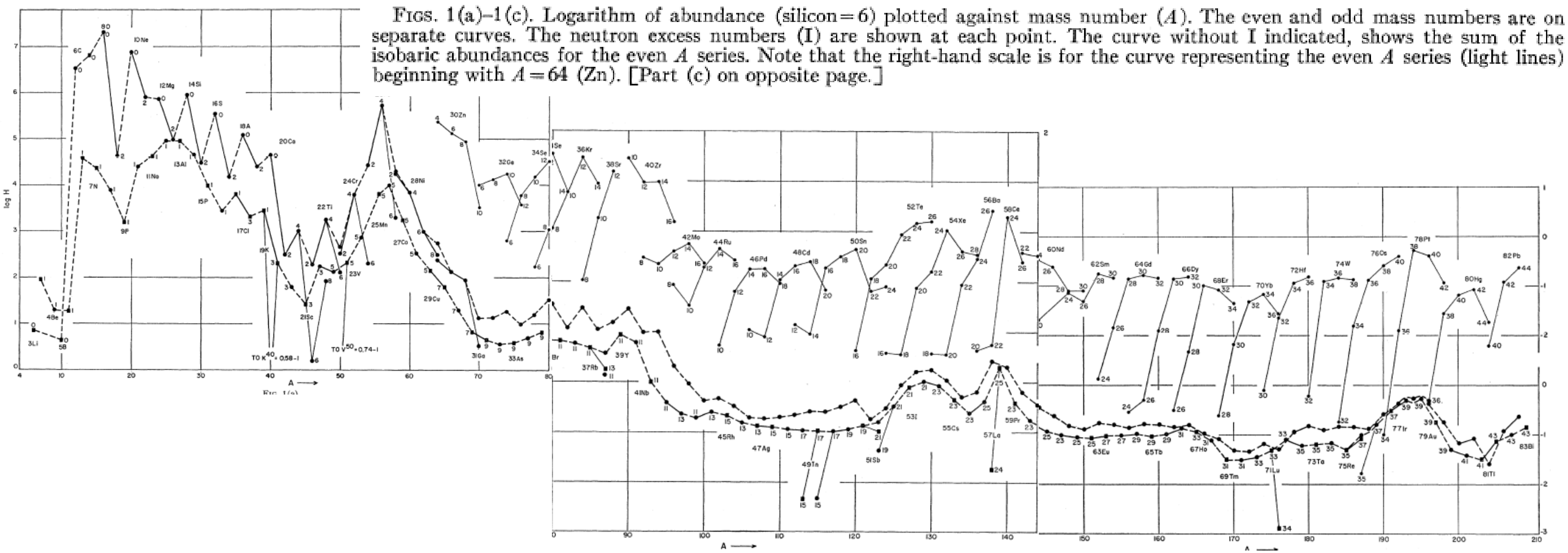
→ No correlation with periodic table of the elements (since 1870 by Medelejeev) ???

1895 Rowland: relative intensities of 39 elemental signatures in solar spectrum

1929 Russell: calibrated solar spectral data to obtain table of abundances

1937 Goldschmidt: First analysis of “primordial” abundances: meteorites, sun

1956 Suess and Urey “Abundances of the Elements”, Rev. Mod. Phys. 28 (1956) 53



FIGS. 1(a)–1(c). Logarithm of abundance (silicon=6) plotted against mass number (*A*). The even and odd mass numbers are on separate curves. The neutron excess numbers (I) are shown at each point. The curve without I indicated, shows the sum of the isobaric abundances for the even *A* series. Note that the right-hand scale is for the curve representing the even *A* series (light lines) beginning with *A*=64 (Zn). [Part (c) on opposite page.]

“Independent of any theory of the origin of the universe, one may try to find indications
For the nature of the last nuclear reaction that took place …going backwards in time
One may then try to find out how the conditions developed under which these reactions
took place. … a cosmogenic model may then be found as an explanation of the course of events.”

“No attempt is made to do this here. However, attention is drawn to evidence which might serve as a basis for future work along these lines.”

1957 Burbidge, Burbidge, Fowler, Hoyle

REVIEWS OF

MODERN PHYSICS

VOLUME 29, NUMBER 4 | OCTOBER, 1957

Synthesis of the Elements in Stars*

E. MARGARET BURBIDGE, G. R. BURBIDGE, WILLIAM A. FOWLER, AND F. HOYLE

Kellogg Radiation Laboratory, California Institute of Technology, and Mount Wilson and Palomar Observatories, Carnegie Institution of Washington, California Institute of Technology, Pasadena, California

"It is the stars, The stars above us, govern our conditions";
(*King Lear*, Act IV, Scene 3)

but perhaps

"The fault, dear Brutus, is not in our stars, But in ourselves,"
(*Julius Caesar*, Act I, Scene 2)

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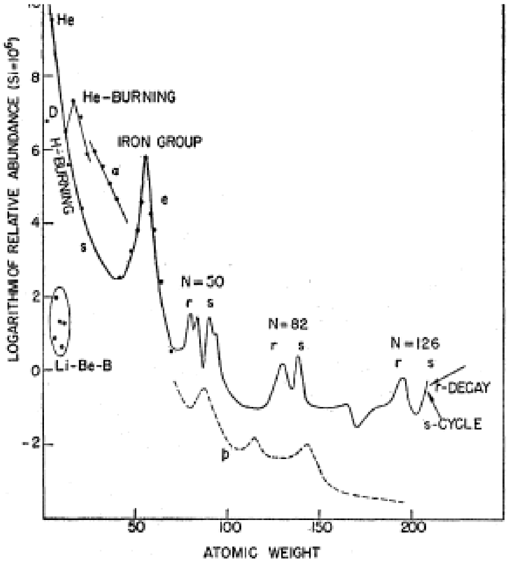
* Supported in part by the joint program of the Office of Naval Research and the U. S. Atomic Energy Commission.



"Man inhibits a universe composed of a great variety of elements and their isotopes …"

1983 Nobel Prize in Physics for Willy Fowler:

KUNGL.
VETENSKAPSAKADEMIEN
THE ROYAL SWEDISH ACADEMY OF SCIENCES

Press Release: The 1983 Nobel Prize in Physics

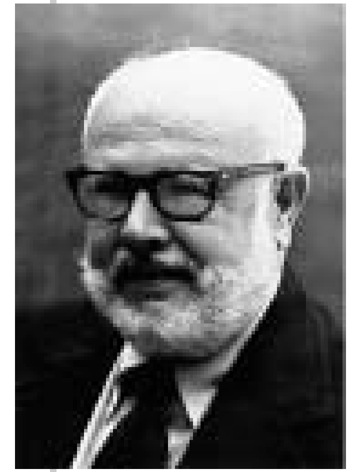
19 October 1983

The Royal Swedish Academy of Sciences has decided to award the 1983 Nobel Prize in Physics by one half to

Professor **Subrahmanyan Chandrasekhar**, University of Chicago, Chicago, USA, **for his theoretical studies of the physical processes of importance to the structure and evolution of the stars,**

and by the other half to

professor **William A. Fowler**, California, Institute of Technology, Pasadena, USA, **for his theoretical and experimental studies of the nuclear reactions of importance in the formation of the chemical elements in the universe.**



3.1. Abundances from stellar spectra (for example the sun):

corona
up to 2 Mio K

hot thin gas
→ **emission lines**

---

chromosphere
~ 10,000 km
up to 10,000 K

hot thin gas
→ **emission lines**

---

photosphere
~ 500 km
~ 6000 K

photons escape freely

still dense enough for photons to excite atoms when frequency matches
→ **absorption lines**

---

convective zone

radiation transport (short photon mean free path)

continuous spectrum

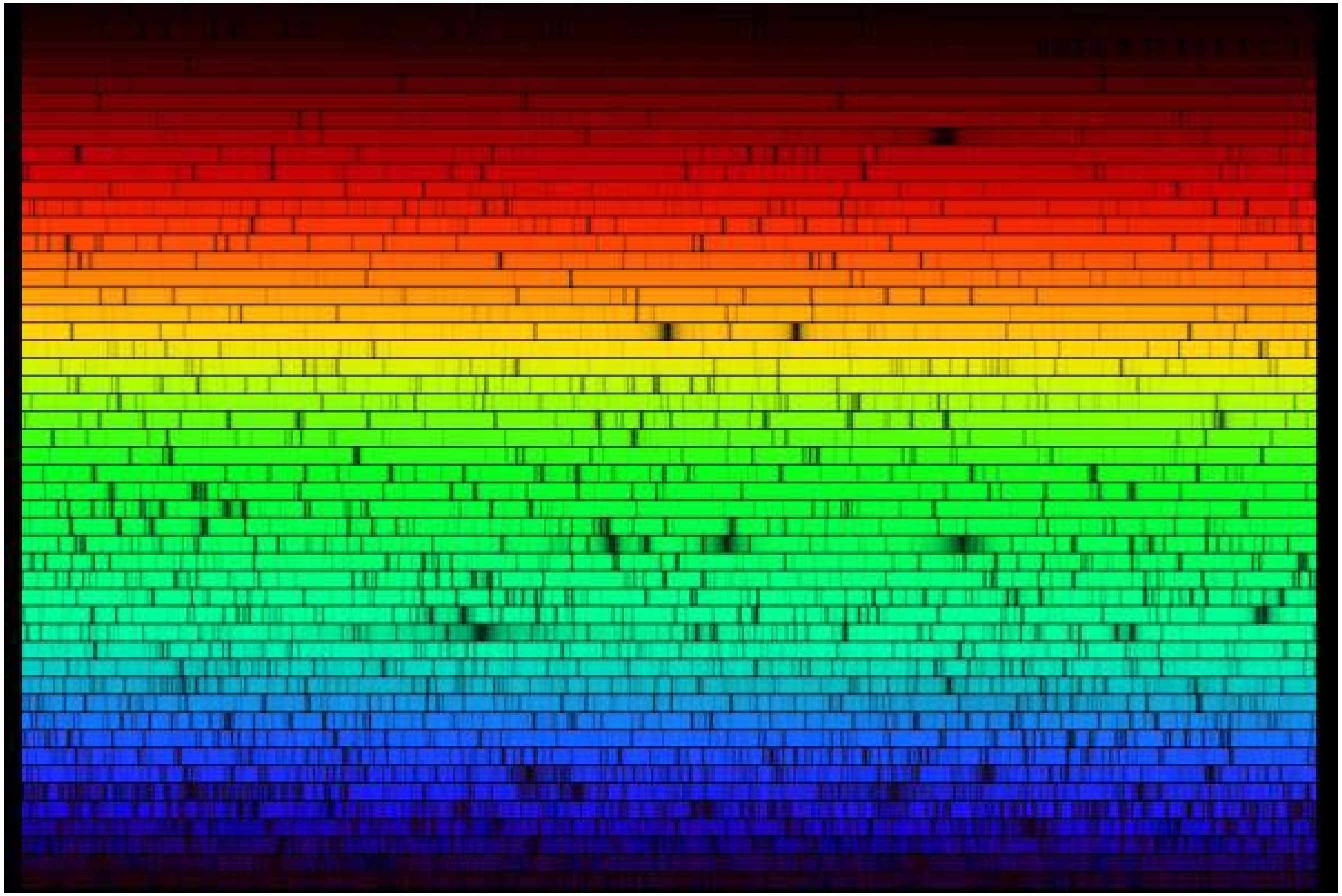
Emission lines from atomic deexcitations
Absorption lines from atomic excitations

} Wavelength -> Atomic Species
Intensity -> Abundance

3.1.1. Absorption Spectra:

provide majority of data because:

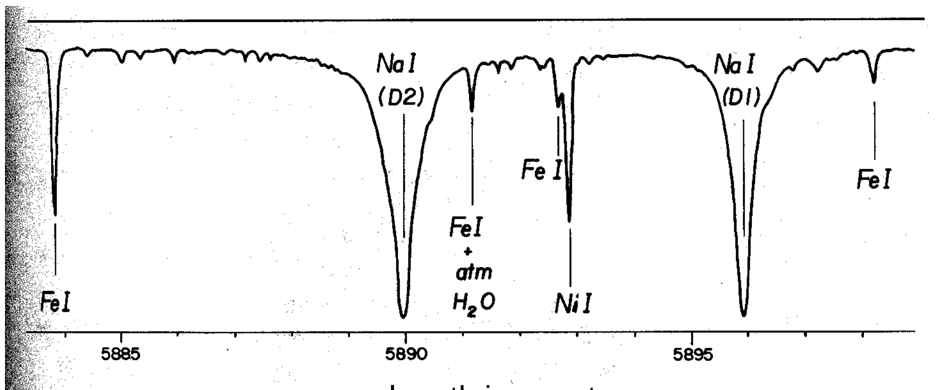
- by far the largest number of elements can be observed
- least fractionation as right at end of convection zone - still well mixed
- well understood - good models available



solar spectrum (Nigel Sharp, NOAO)

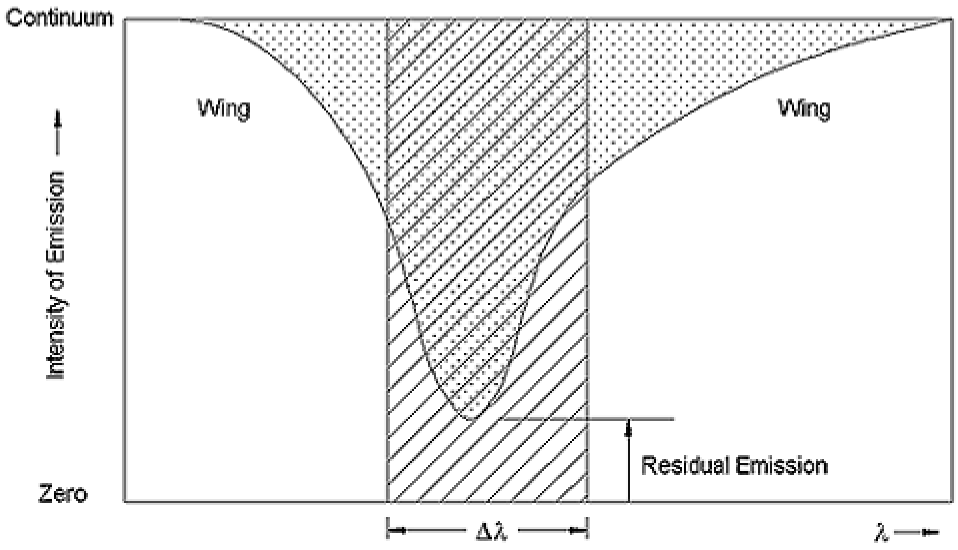
Each line originates from absorption from a specific atomic transition in a specific atom/ion:

portion of the solar spectrum (from Pagel Fig 3.2.)



wavelength in angstrom

Fe I: neutral ion
FeII: singly ionized iron ion
…



effective line width ~ total absorbed intensity

Simple model consideration for absorption in a slab of thickness Δx:

$$I = I_0 \, e^{-\sigma \, n \Delta x}$$

I, I_0 = observed and initial intensity

σ = absorption cross section

n = number density of absorbing atom

So if one knows σ one can determine n and get the abundances

There are 2 complications:

Complication (1) Determine σ

The cross section is a measure of how likely a photon gets absorbed when an atom is bombarded with a flux of photons (more on cross section later …)

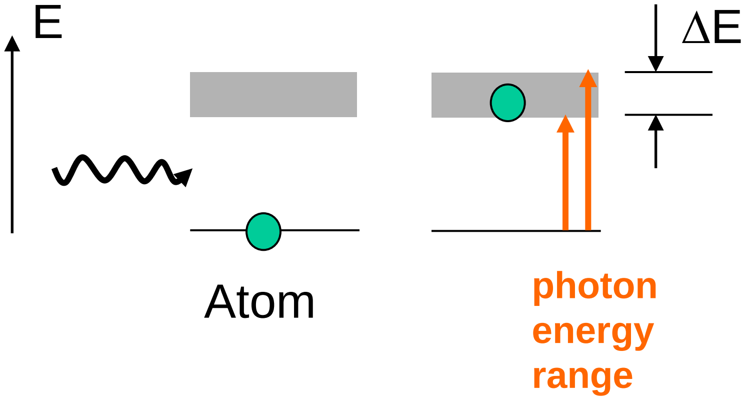
It depends on:

- **Oscillator strength**: a quantum mechanical property of the atomic transition

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

- **Line width**

  the wider the line in wavelength, the more likely a photon is absorbed (as in a classical oscillator).



excited state has an energy width ΔE. This leads to a range of photon energies that can be absorbed and to a line width

Heisenbergs uncertainty principle relates that to the **lifetime** τ of the excited state

$$\Delta E \cdot \tau = \hbar$$

→ need lifetime of final state

The lifetime of an atomic level in the stellar environment depends on:

- **The natural lifetime** (natural width)

  lifetime that level would have if atom is left undisturbed

- **Frequency of Interactions of atom with other atoms or electrons**

  Collisions with other atoms or electrons lead to deexcitation, and therefore to a shortening of the lifetime and a broadening of the line

  Varying electric fields from neighboring ions vary level energies through Stark Effect

  → depends on **pressure**

  → need local **gravity**, or **mass/radius** of star

- **Doppler broadening** through variations in atom velocity

  - thermal motion → depends on **temperature**
  - micro turbulence

Need detailed and accurate model of stellar atmosphere !

Complication (2)

Atomic transitions depend on the state of ionization !

The number density n determined through absorption lines is therefore the number density of ions in the ionization state that corresponds to the respective transition.

to determine the total abundance of an atomic species one needs the fraction of atoms in the specific state of ionization.

Notation: I = neutral atom, II = one electron removed, III=two electrons removed …..

Example: a CaII line originates from singly ionized Calcium

Example: determine abundance of single ionized atom through lines.

need n_+/n_0 to determine total abundance $n_+ + n_0$

n_+: number density of atoms in specific state of ionization
n_0: number density of neutral atoms

We assume local thermodynamic equilibrium **LTE**, which means that the ionization and recombination reactions are in thermal equilibrium:

$$A \longleftrightarrow A^+ + e^-$$

This is maintained by frequent collisions in hot gas
But not always !!!

Then the **Saha Equation** yields:

$$\frac{n_+ n_e}{n_0} = \left(\frac{2\pi m_e kT}{h^2}\right)^{3/2} \frac{g_+ g_e}{g_0} e^{-\frac{B}{kT}}$$

n_e = electron number density
m_e = electron mass
B = electron binding energy
g = statistical factors (2J+1)

need pressure and temperature

strong temperature dependence !

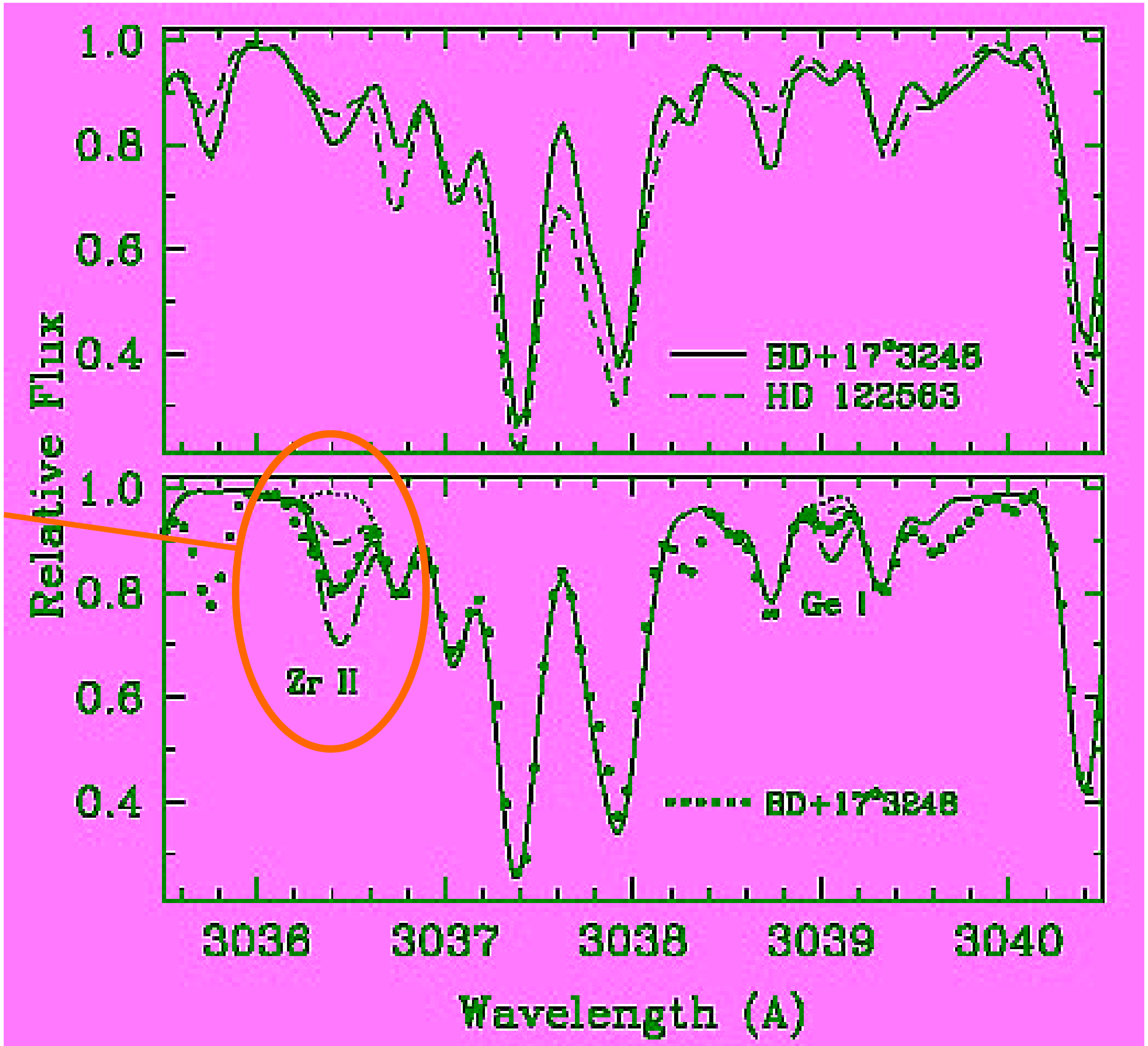
with higher and higher temperature more ionized nuclei - of course eventually a second, third, … ionization will happen.

again: one needs a detailed and accurate stellar atmosphere model

Practically, one sets up a stellar atmosphere model, based on star type, effective temperature etc. Then the parameters (including all abundances) of the model are fitted to best reproduce all spectral features, incl. all absorption lines (can be 100's or more) .

Example for a r-process star (Sneden et al. ApJ 572 (2002) 861)

varied ZrII abundance



3.1.2. Emission Spectra:

Disadvantages:

- **less understood, more complicated solar regions**
  (it is still not clear how exactly these layers are heated)
- **some fractionation/migration effects**
  for example FIP: species with low first ionization potential
  are enhanced in respect to photosphere
  possibly because of fractionation between ions and neutral atoms

Therefore abundances less accurate

But there are elements that cannot be observed in the photosphere
(for example helium is only seen in emission lines)

this is how Helium was discovered by Sir Joseph Lockyer of England in 20 October 1868.

Solar Chromosphere red from Hα emission lines

Complication (3)

All solar spectroscopic methods determine the **PRESENT DAY** composition on the surface of the sun

The solar abundances are defined as the composition of the presolar nebula

Diffusion effects modify the surface composition !!!
(can be accounted for by solar models that calculate the evolution from the Initial bulk composition of the sun to the present day surface composition)

3.2. Meteorites

Meteorites can provide accurate information on elemental abundances in the presolar nebula. More precise than solar spectra if data are available …

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

Not all meteorites are suitable - most of them are fractionated and do not provide representative solar abundance information.

One needs primitive meteorites that underwent little modification after forming.

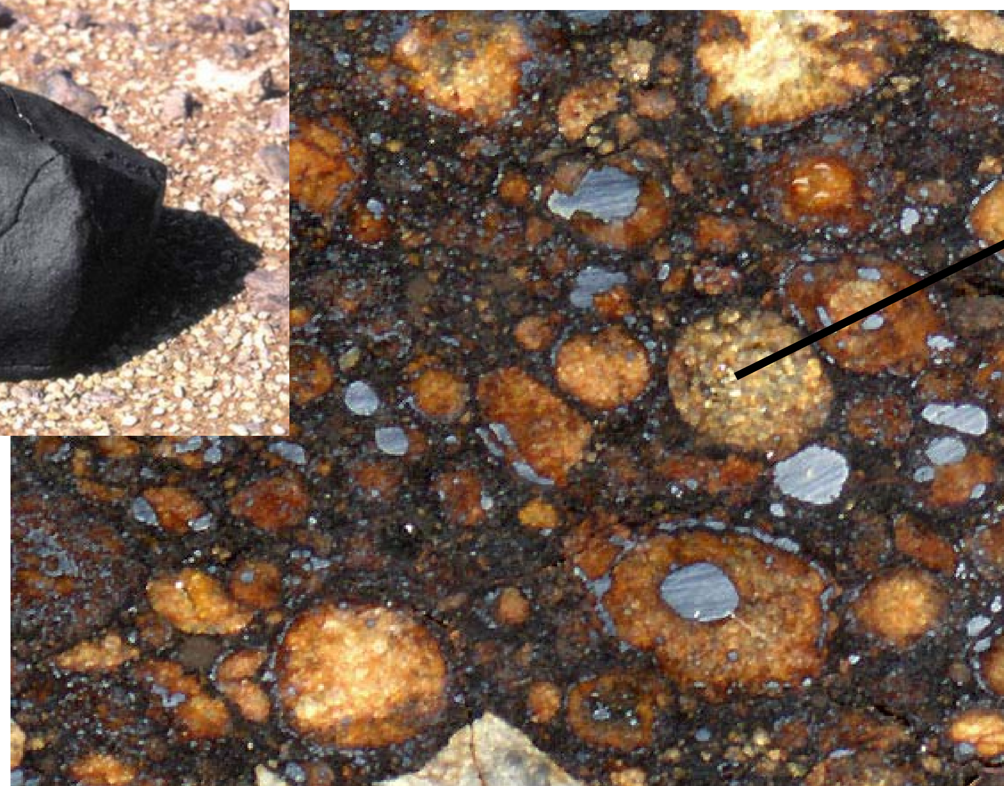
Classification of meteorites:

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

Use **carbonaceous chondrites** (~6% of falls)

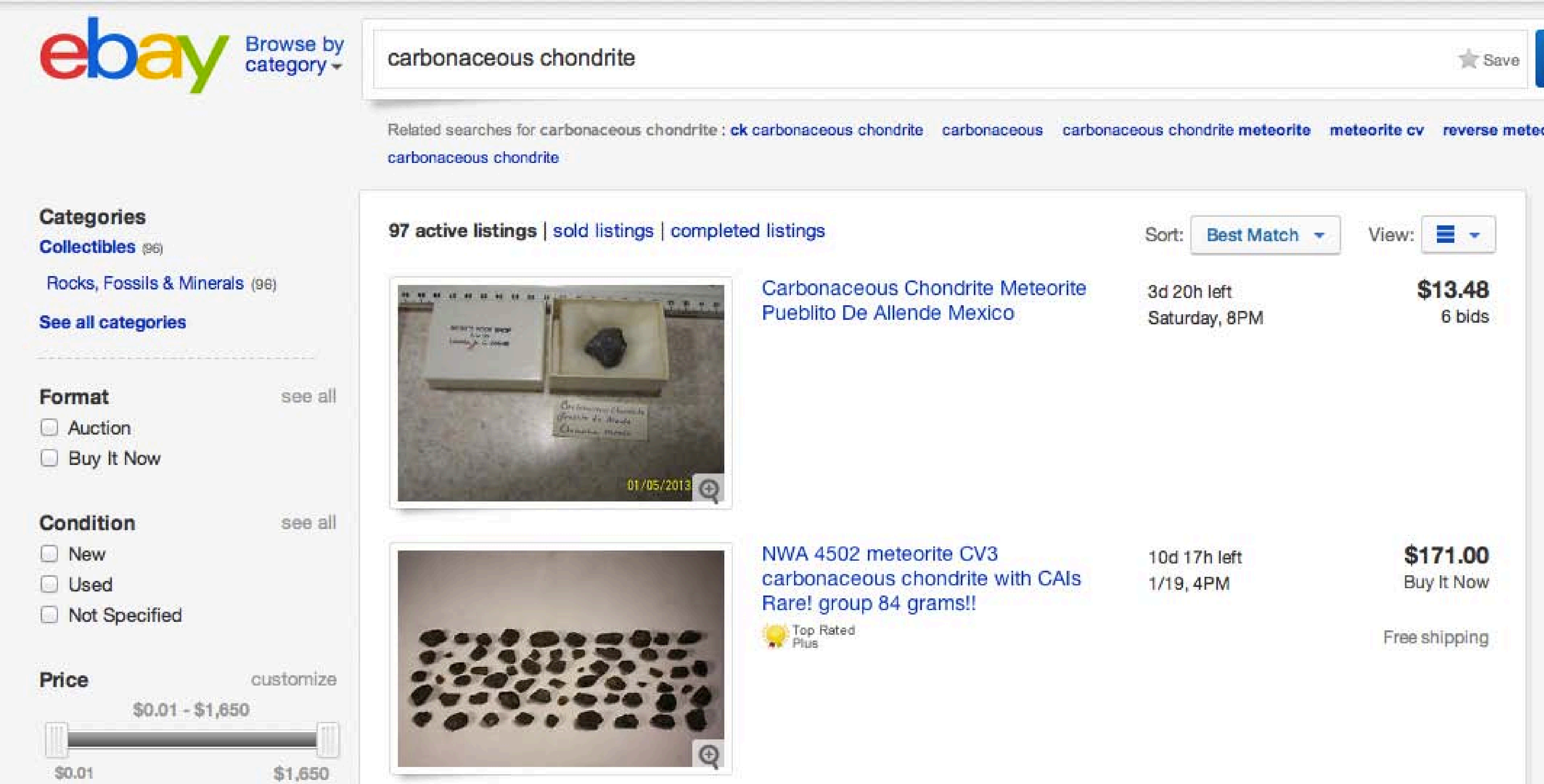
Chondrites: Have Chondrules - small ~1mm size shperical inclusions in matrix
believed to have formed very early in the presolar nebula
accreted together and remained largely unchanged since then

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



How find them ?

How can we find carbonaceous chondrites?



more on meteorites

http://www.saharamet.com
http://www.meteorite.fr

Not all carbonaceous chondrites are equal

(see http://www.daviddarling.info/encyclopedia/C/carbchon.html for a nice summary)

There are CI, CM, CV, CO, CK, CR, CH, CB, and other chondites

CI Chondites (~3% of all carbonaceous chondrites)

- are considered to be the least altered meteorites available
- Some chemical alterations but assumed to occur in closed system so no change of overall composition
- named after Ivuna Meteorite (Dec 16, 1938 in Ivuna, Tanzania, 705g)

- **only 5 known – only 4 suitably large (Alais, Ivuna, Orgueil, Revelstoke, Tonk)**
- see Lodders et al. Ap. J. 591 (2003) 1220 for a recent analysis