Lecture 2

A) Using the IMF

B) Abundances in Nature

Initial Mass Function and Typical Supernova Masses

The initial mass function (IMF) is defined as that number of stars that have ever formed per unit area of the Galactic disk (pc^{-2}) per unit logarithmic (base 10) interval (earlier was per volume pc^{-3})

$$\text{IMF} = \xi(\log M)$$

The product $\xi(\log M_1) \times (\Delta \log M)$ is thus the number of stars in the mass interval $\Delta \log M$ around $\log M_1$ ever formed per unit area (pc^{-2}) in our Galaxy.

An interval of ± 0.3 around $\log M_1$ thus corresponds to a range in masses $M_1 / 2$ to $2\ M_1$.

For low mass stars, $\tau_{MS} > \tau_{Gal}$ (i.e. $M < 0.8\ M_{\odot}$), the IMF equals the present day mass function (PDMF). For higher mass stars an uncetain correction must be applied.

There are many IMFs in the literature. Here to get some simple results that only depend on the slope of the IMF above 10 solar masses, we will use the one from Salpeter (1955), which remains appropriate for massive stars, as well as one taken from Shapiro and Teukolsky's textbook (Chap 1.3, page 9) for a more extended mass interval. This latter IMF is an amalgamation of Bahcall and Soneira (ApJS, 44, 73, (1980)) and Miller and Scalo (ApJS, 41, 513, (1979))

$$\log\,\xi(\log M) = 1.41 - 0.9\log M - 0.28(\log M^2)$$

A related quantity is the slope of the IMF

$$\Gamma = \frac{d\log\xi}{d\log M} = -0.9 - 0.56\log M$$

Salpeter, in his classic treatment took $\Gamma = \text{const.} = -1.35$

Salpeter (1955)
(7 pages large type)

[4668 citations as of 3/29/15]

$$dN = \xi(\log M)\, d(\log_{10} M)\, \frac{dt}{T_0}$$

where T_0 is the age of the galaxy and dN is the number of stars in the mass range $d \log M$ created per cubic pc in time dt

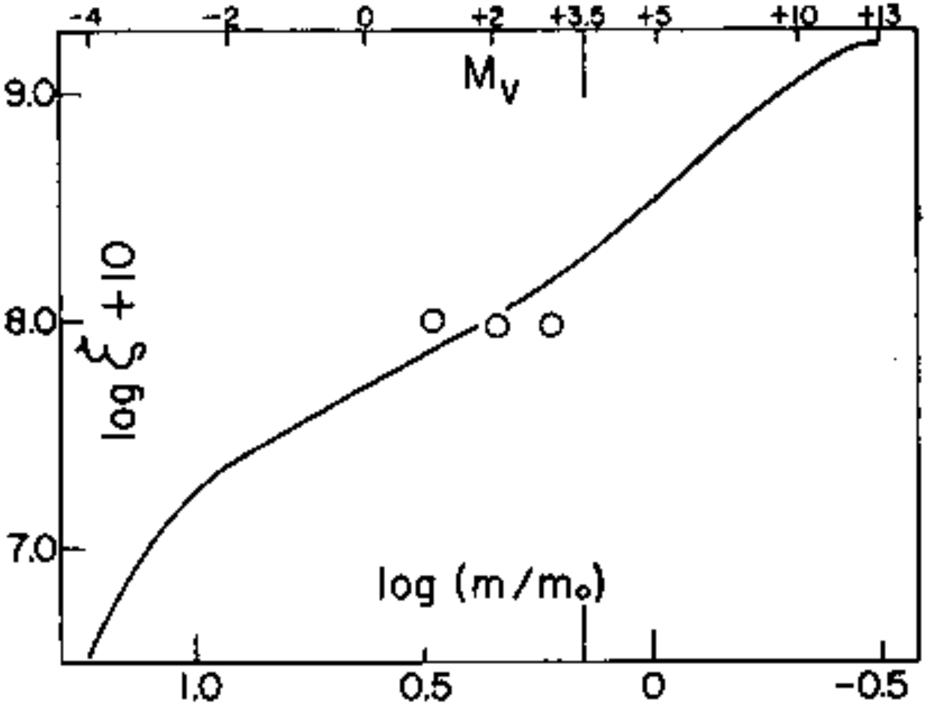


FIG. 2.—The logarithm of the "original mass function," ξ, plotted against the mass, 𝔐, in solar units.

For $\log\left(\frac{M}{M_\odot}\right)$ between -0.4 and +1.0

M between 0.4 and 10

$$\xi(\log \mathrm{M}) \approx 0.03 \left(\frac{M}{M_\odot}\right)^{-1.35}$$

Examples of how to use the IMF

Suppose you want to know the fraction by number of all stars ever born having mass $\geq$ M (Here M_U equals the most massive star is taken to be 100 $M_\odot$; M_L, the least massive star, is taken to be 0.1)

$$F_n(M) = \frac{\int_{M}^{M_U} \xi(\log M)\, d\log M}{\int_{M_L}^{M_U} \xi(\log M)\, d\log M} = 1/2$$

We use the Shapiro-Teukolsky IMF here because the Salpeter IMF is not good below about 0.5 solar mass. The answer is 0.3 solar masses. Half of the stars ever born were above 0.3 solar masses and half were below

Examples of how to use the IMF

How about the total fraction of mass ever incorporated into stars with masses greater than M?

$$X_m(M) = \frac{\int_{M}^{M_U} M\ \xi(\log M)\, d\log M}{\int_{M_L}^{M^U} M\, \xi(\log M)\, d\log M}$$

This quantity is 0.5 for a larger value of M, 1.3 $M_\odot$. Half the mass went into stars lighter than 1.3, half into heavier stars.

For simplicity in what follows use a Salpeter IMF, take Γ=-1.35, then $\varsigma(\log M)=C_0 M^{\Gamma}$ and

$$\varsigma(\log M)\ \ d\log M = C'M^{\Gamma}\,\frac{dM}{M} = C'\frac{dM}{M^{1-\Gamma}} = C'\frac{dM}{M^{2.35}}$$

What is the number fraction greater than M?

$$F_n(M) = \frac{\int\limits_{M}^{M_U} \frac{dM}{M^{1-\Gamma}}}{\int\limits_{M_L}^{M_U} \frac{dM}{M^{1-\Gamma}}} = \frac{M_U^{\Gamma} - M^{\Gamma}}{M_U^{\Gamma} - M_L^{\Gamma}}$$

For $\Gamma = -1.35$ for example and $M_U = 100$, and $M_L = 0.1$, the number fraction greater than 10 $M_\odot$ is 0.2% and the number fraction greater than 25 $M_\odot$ is 0.06%. Simi-

5

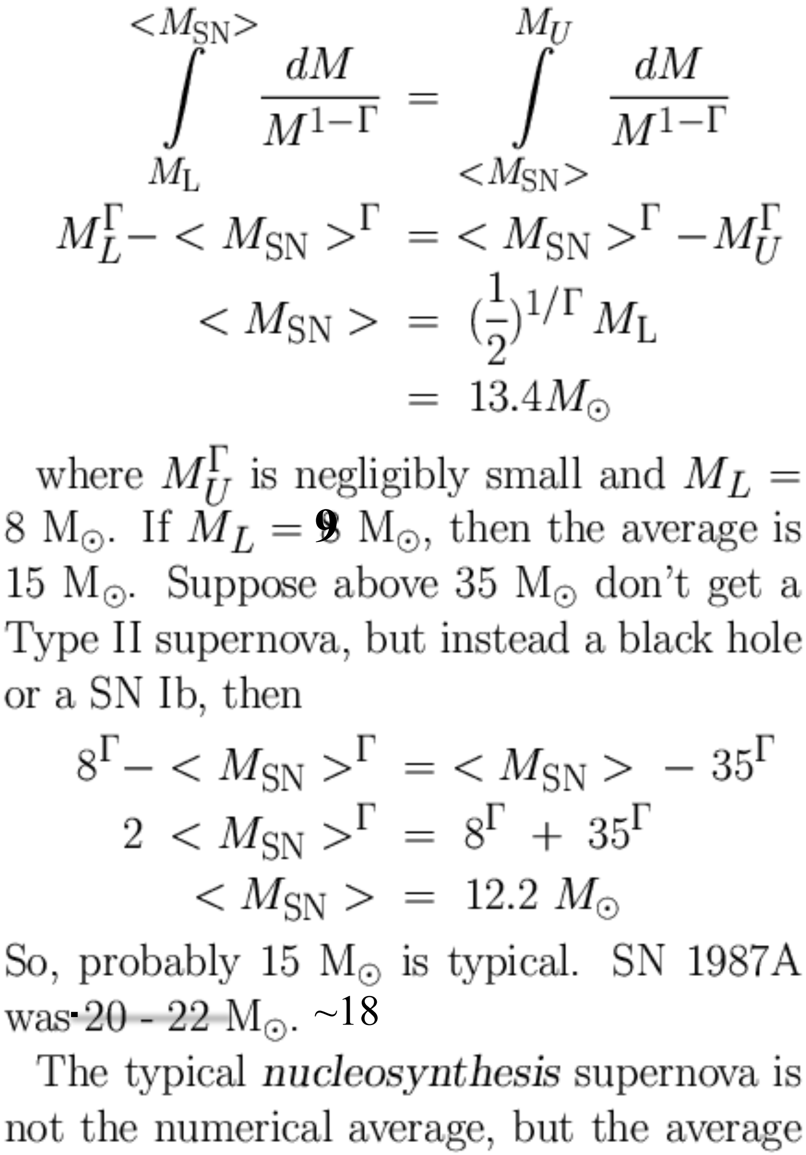
.05%

The mass weighted average tells us the fraction of the mass incorporated into stars above some value

$$X_m(M) = \frac{\int\limits_{M}^{M_U} \frac{(M)dM}{M^{1-\Gamma}}}{\int\limits_{M_L}^{M_U} \frac{(M)dM}{M^{1-\Gamma}}} = \frac{M_U^{\Gamma+1} - M^{\Gamma+1}}{M_U^{\Gamma+1} - M_L^{\Gamma+1}}$$

This gives 12% for 10 $M_\odot$, and 6.1% for 25 $M_\odot$.

The average supernova by number is then



$$\int_{M_{\rm L}}^{<M_{\rm SN}>} \frac{dM}{M^{1-\Gamma}} = \int_{<M_{\rm SN}>}^{M_U} \frac{dM}{M^{1-\Gamma}}$$

$$M_L^\Gamma - < M_{\rm SN} >^\Gamma = < M_{\rm SN} >^\Gamma - M_U^\Gamma$$

$$< M_{\rm SN} > = (\frac{1}{2})^{1/\Gamma} M_{\rm L}$$

$$= 13.4 M_\odot$$

where M_U^Γ is negligibly small and $M_L = 8$ M$_\odot$. If $M_L = 9$ M$_\odot$, then the average is 15 M$_\odot$. Suppose above 35 M$_\odot$ don't get a Type II supernova, but instead a black hole or a SN Ib, then

$$8^\Gamma - < M_{\rm SN} >^\Gamma = < M_{\rm SN} > - 35^\Gamma$$

$$2 < M_{\rm SN} >^\Gamma = 8^\Gamma + 35^\Gamma$$

$$< M_{\rm SN} > = 12.2 M_\odot$$

So, probably 15 M$_\odot$ is typical. SN 1987A was ~~20 - 22~~ M$_\odot$. ~18

The typical *nucleosynthesis* supernova is not the numerical average, but the average

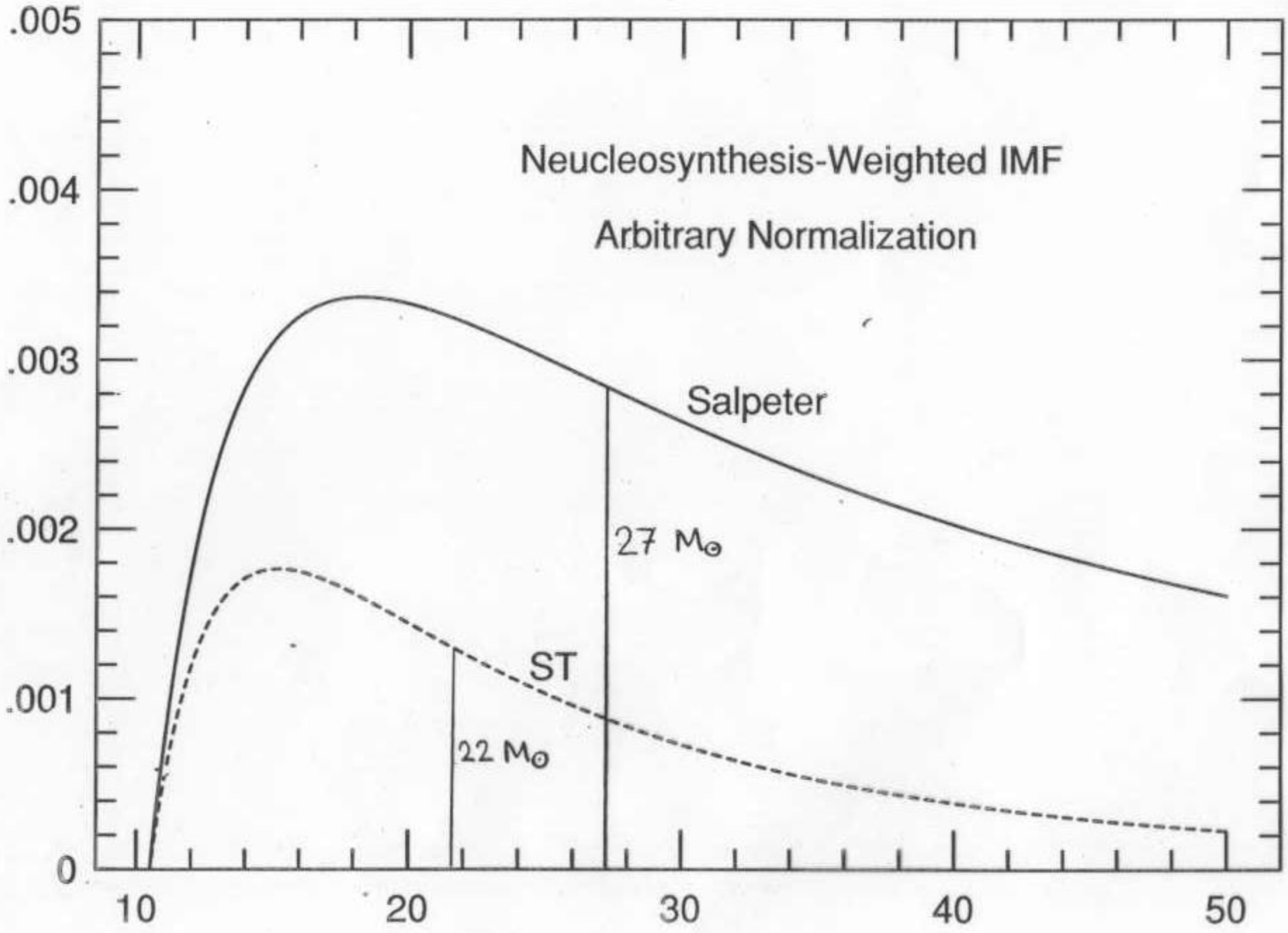
$$\int \frac{dM}{M^{1-\Gamma}} = \int M^{\Gamma-1}\, dM = \frac{M^\Gamma}{\Gamma}$$

For homework
evaluate using
Smartt's limit of 20

weighted by the mass ejected in heavy elements. That is

$$\int_{10}^{M} \frac{dM}{M^{-\Gamma}} Z_{\mathrm{ej}} = \int_{M}^{M_U} \frac{dM}{M^{-\Gamma}} Z_{\mathrm{ej}}$$

where Z_{ej} is the fraction of a star's mass ejected in the form of heavy elements. A 40 $\mathrm{M}_\odot$ supernova ejects about 11 $\mathrm{M}_\odot$of heavy elements (neglecting mass loss); an 11 $\mathrm{M}_\odot$ supernova ejects almost none. Woosley and Weaver (*Ann NY Acad.*, 336, 347, (1986)) find $Z_{\mathrm{ej}} \approx 0.4 - 4.2(M_\odot/M)$ for $M \gtrsim 11$ $\mathrm{M}_\odot$. The result depends upon M_U and the choice of Γ, but is typically ~ 25 $\mathrm{M}_\odot$. This motivates our particular interest in stars of this main sequence mass.


Neucleosynthesis-Weighted IMF
Arbitrary Normalization
Salpeter
ST
27 M⊙
22 M⊙
.005
.004
.003
.002
.001
0
10
20
30
40
50

Abundances in Nature

Any study of nucleosynthesis must have one of its key objectives a physical explanation for the pattern of abundances that we find in nature -- in the solar system (i.e., the sun) and in other locations in the cosmos (other stars, the ISM, cosmic rays, IGM, and other galaxies)

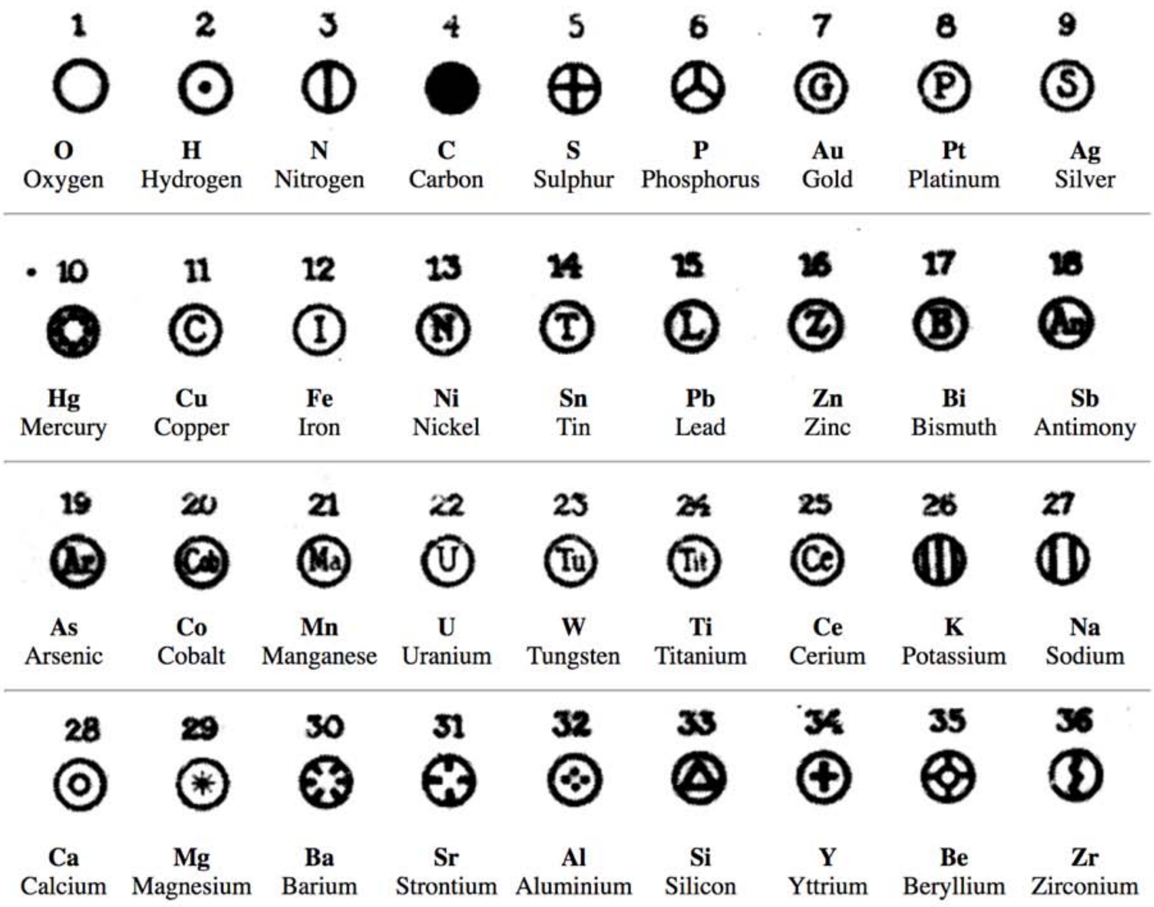
Key to that is knowing the pattern in the sun and meteorites.

For solar abundances there are three main sources:

- The Earth - good for isotopic composition only
- The solar spectrum
- Meteorites, especially primitive ones

Dalton (1808)
36 elements

118 today



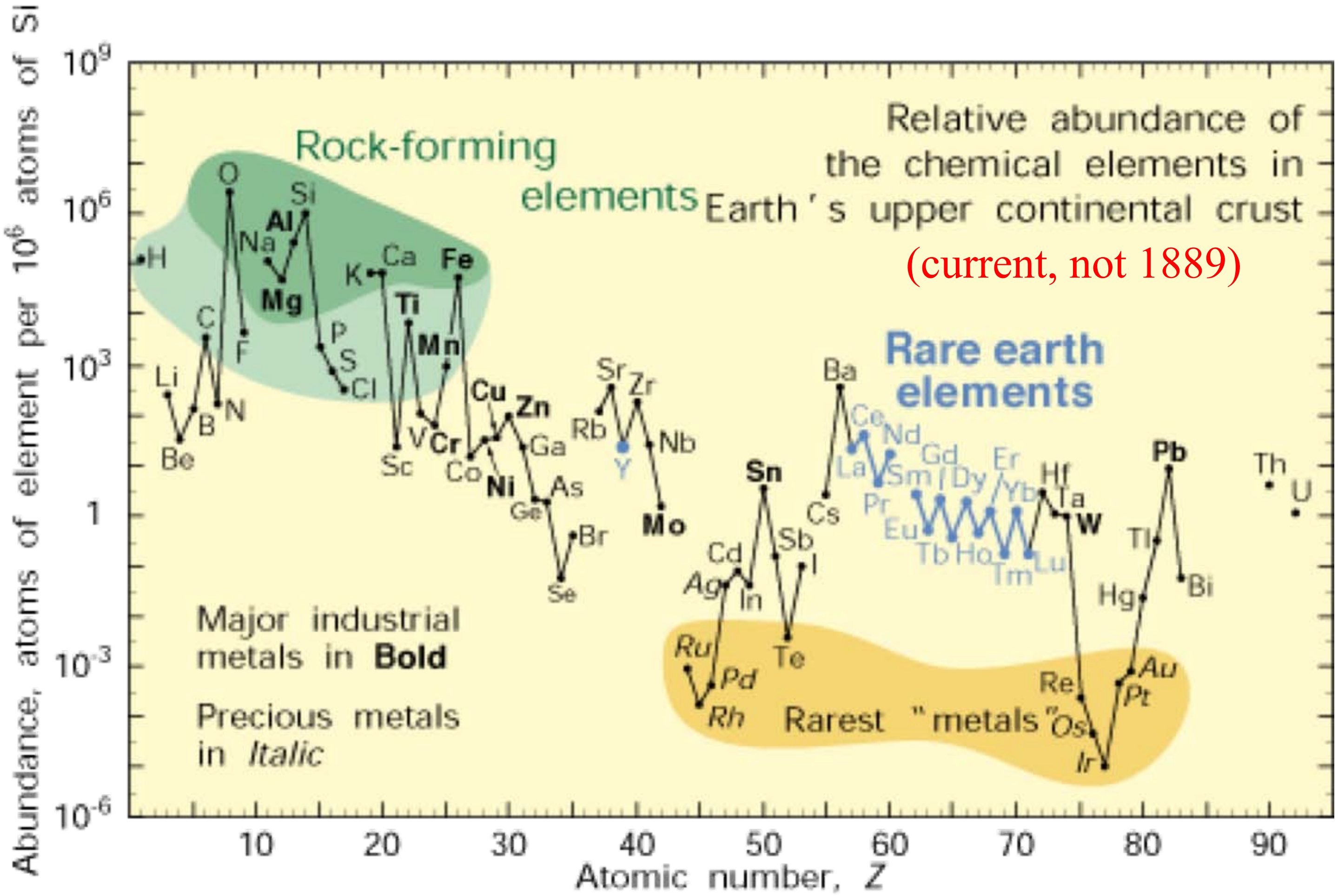
1 O Oxygen	2 H Hydrogen	3 N Nitrogen	4 C Carbon	5 S Sulphur	6 P Phosphorus	7 Au Gold	8 Pt Platinum	9 Ag Silver
10 Hg Mercury	11 Cu Copper	12 Fe Iron	13 Ni Nickel	14 Sn Tin	15 Pb Lead	16 Zn Zinc	17 Bi Bismuth	18 Sb Antimony
19 As Arsenic	20 Co Cobalt	21 Mn Manganese	22 U Uranium	23 W Tungsten	24 Ti Titanium	25 Ce Cerium	26 K Potassium	27 Na Sodium
28 Ca Calcium	29 Mg Magnesium	30 Ba Barium	31 Sr Strontium	32 Al Aluminium	33 Si Silicon	34 Y Yttrium	35 Be Beryllium	36 Zr Zirconium

33 elements – 1789 – Lavoisier

50 elements - 1869 – Mendeleev
Periodic table

History:

1863, William Huggins – first stellar spectra. Same elements in stars as earth
1889, Frank W. Clarke read a paper before the Philosophical Society of Washington “The Relative Abundance of the Chemical Elements” This was of necessity just about the earth



(current, not 1889)

Current “abundance” distribution of elements in the earths crust:

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

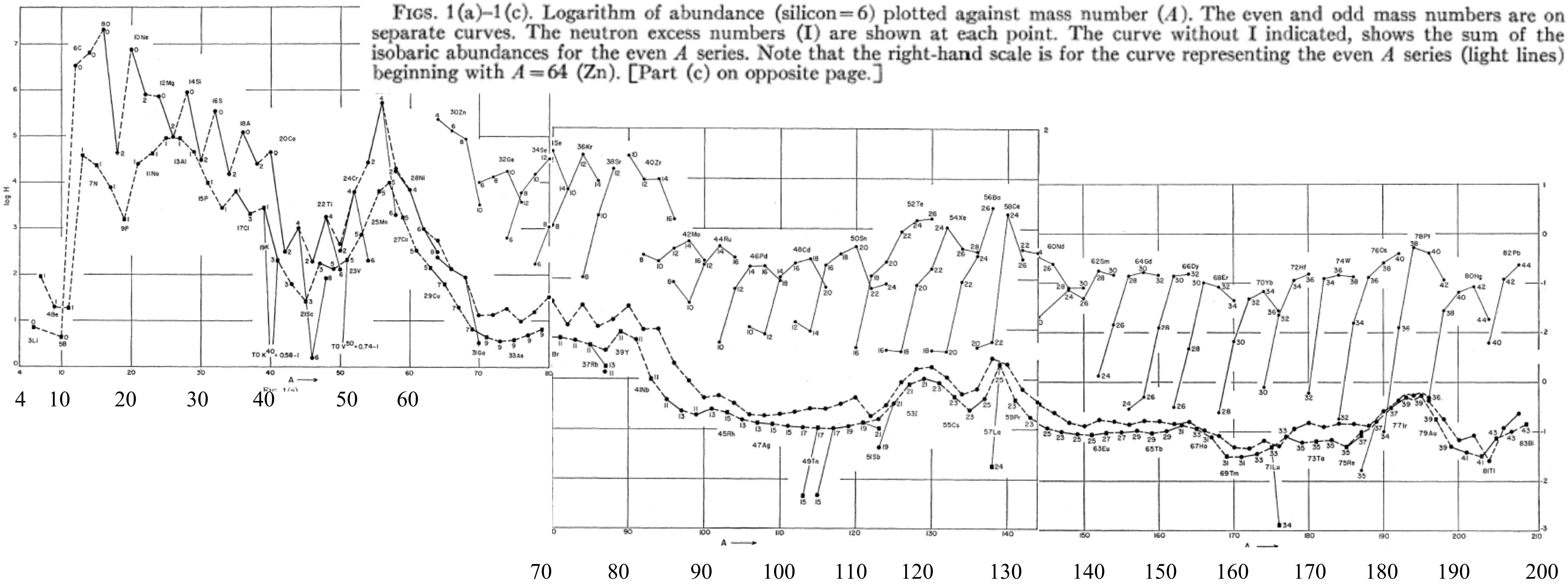
1925 Payne-Gaposchin – PhD - sun is mainly composed of hydrogen

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

(**1932** Chadwick – the neutron **1938** – Bethe and Critchfield – hydrogen burning)

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

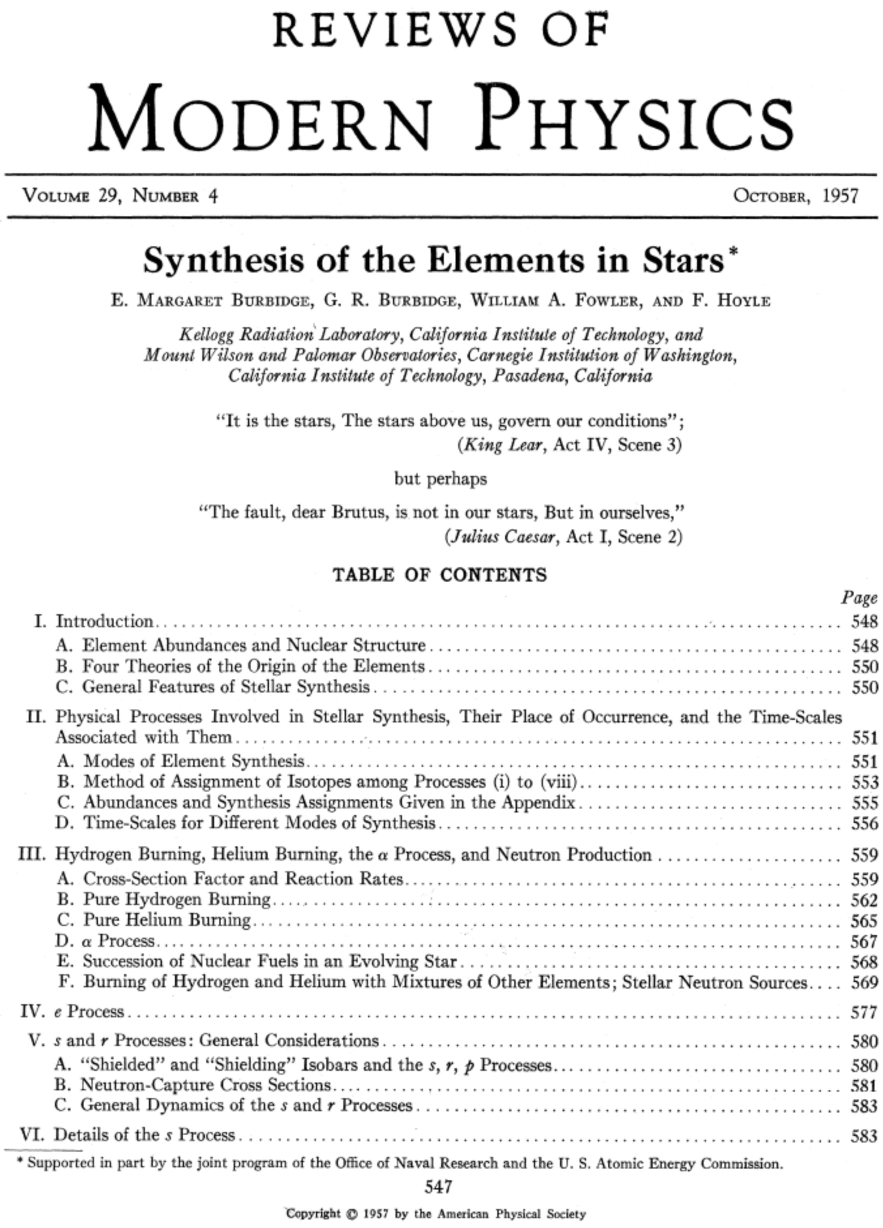
1956 Suess and Urey “Abundances of the Elements”, Rev. Mod. Phys. 28 (1956) 53



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.]

A landmark publication Suess and Urey tabulated results from many prior works plus their own. Noted systematics correlated with nuclear properties. E.g. smoothness of the odd-A isotopic abundance plot.

1957 Burbidge, Burbidge, Fowler, Hoyle



REVIEWS OF
MODERN PHYSICS

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Synthesis of the Elements in Stars*

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"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.

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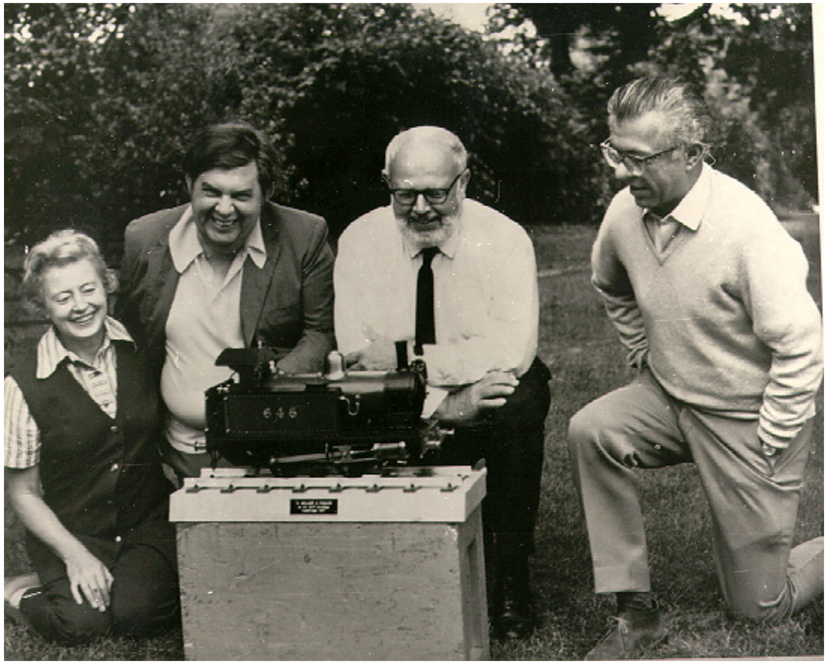
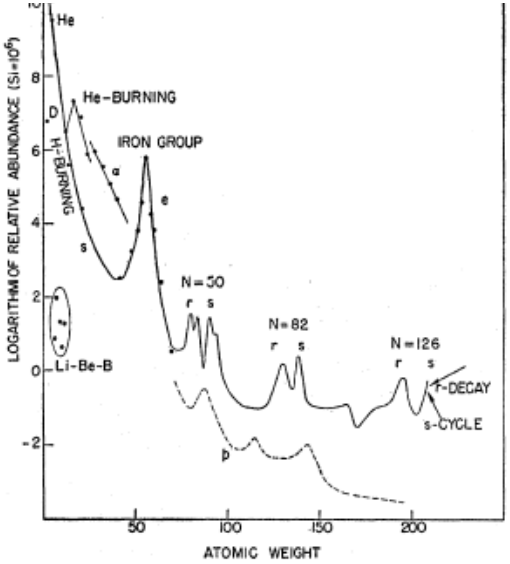
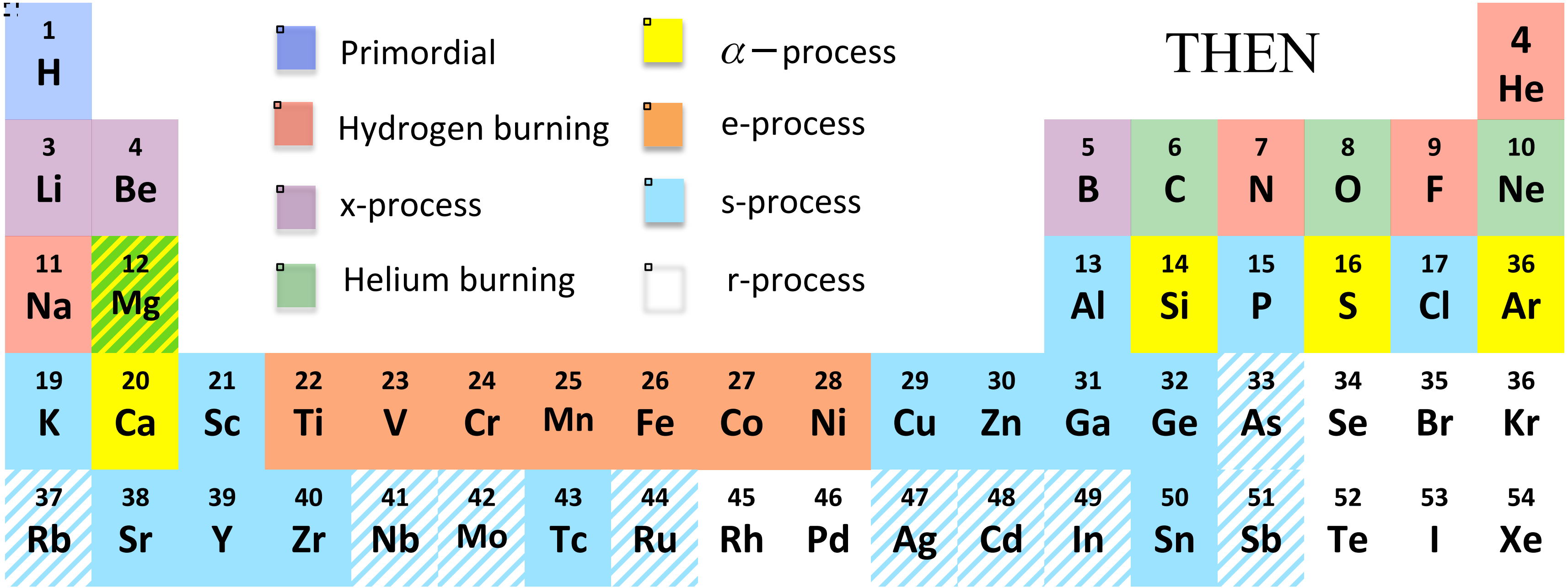
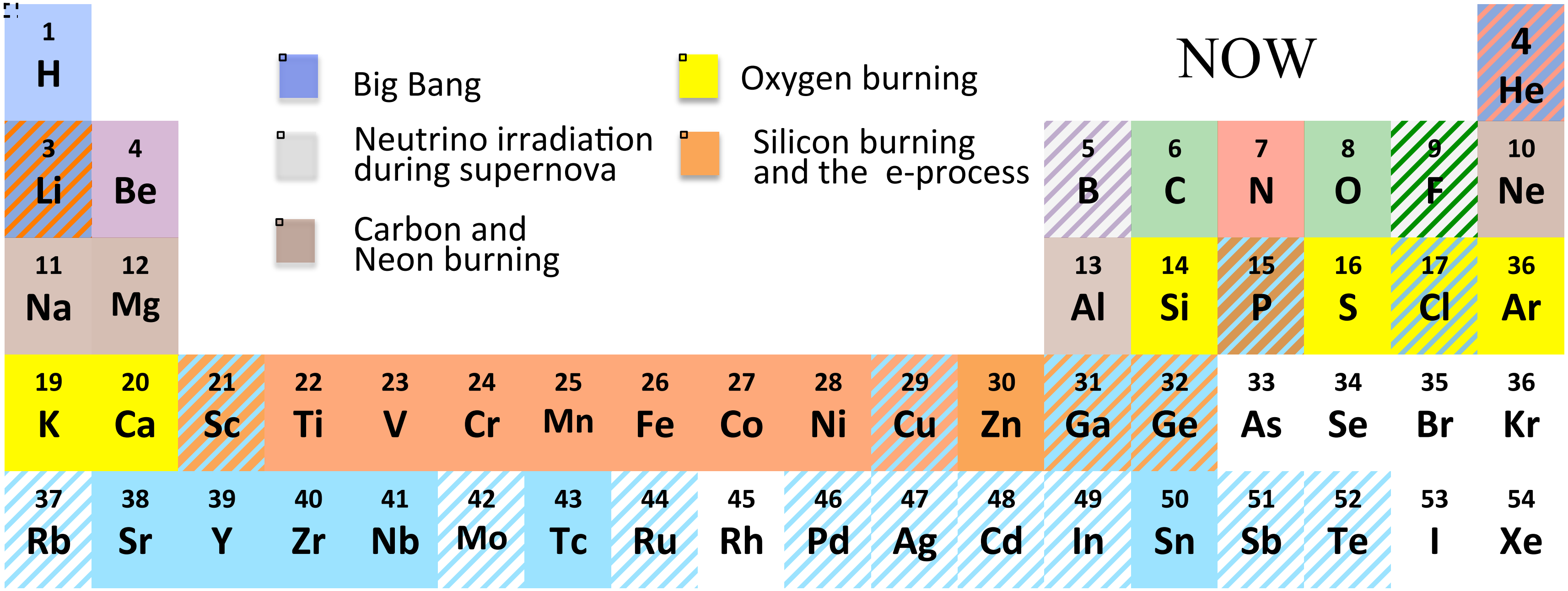




H. Schatz


THEN
Primordial
Hydrogen burning
x-process
Helium burning
α−process
e-process
s-process
r-process
1 H
4 He
3 Li
4 Be
5 B
6 C
7 N
8 O
9 F
10 Ne
11 Na
12 Mg
13 Al
14 Si
15 P
16 S
17 Cl
36 Ar
19 K
20 Ca
21 Sc
22 Ti
23 V
24 Cr
25 Mn
26 Fe
27 Co
28 Ni
29 Cu
30 Zn
31 Ga
32 Ge
33 As
34 Se
35 Br
36 Kr
37 Rb
38 Sr
39 Y
40 Zr
41 Nb
42 Mo
43 Tc
44 Ru
45 Rh
46 Pd
47 Ag
48 Cd
49 In
50 Sn
51 Sb
52 Te
53 I
54 Xe


NOW
Big Bang
Neutrino irradiation during supernova
Carbon and Neon burning
Oxygen burning
Silicon burning and the e-process
1 H
4 He
3 Li
4 Be
5 B
6 C
7 N
8 O
9 F
10 Ne
11 Na
12 Mg
13 Al
14 Si
15 P
16 S
17 Cl
36 Ar
19 K
20 Ca
21 Sc
22 Ti
23 V
24 Cr
25 Mn
26 Fe
27 Co
28 Ni
29 Cu
30 Zn
31 Ga
32 Ge
33 As
34 Se
35 Br
36 Kr
37 Rb
38 Sr
39 Y
40 Zr
41 Nb
42 Mo
43 Tc
44 Ru
45 Rh
46 Pd
47 Ag
48 Cd
49 In
50 Sn
51 Sb
52 Te
53 I
54 Xe

Since 1956 many more surveys by e.g.,

Cameron (1970,1973)

Anders and Ebihara (1982); Grevesse (1984)

Anders and Grevesse (1989) – the standard for a long time

Grevesse and Sauval (1998)

Lodders (2003, 2009, 2014, 2018)

Asplund, Grevesse and Sauval (2009, 2010; ARAA)

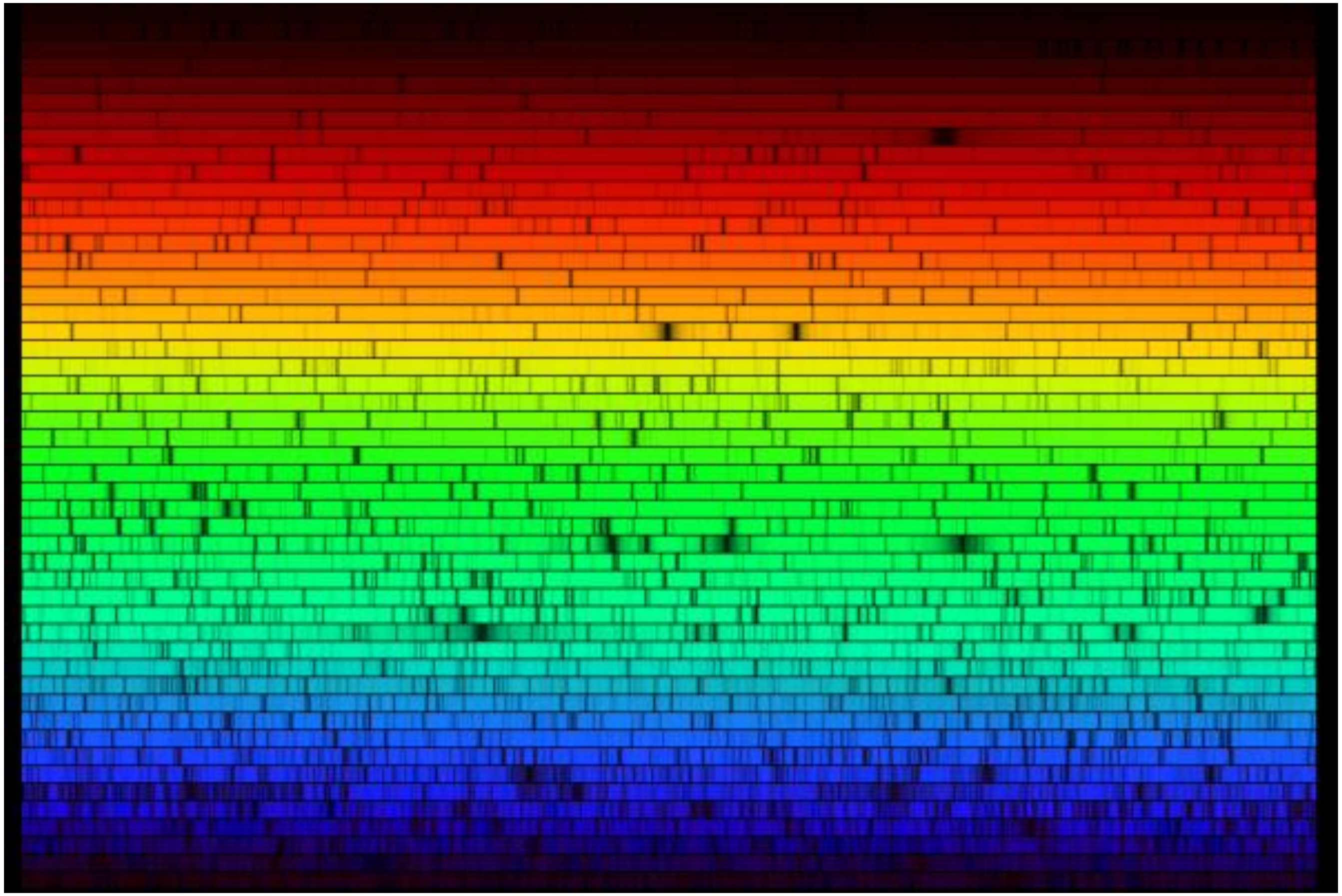
see class website for papers

http://www.ucolick.org/~woosley/ay220papers.html

Absorption Spectra:

83 includes U, Th, Bi, not Tc or Pm

- 68 out of 83 stable or long lived elements have been observed in the sun
- small fractionation - convective surface - well mixed
- reasonably well understood - good 3D models available



solar spectrum (Nigel Sharp, NOAO)

Complications

- **Oscillator strengths**:

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

- **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 (2009) on class website.

H. Schatz

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 with 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

Noble Gases: (see Asplund et al 2009)

- Helium – helioseismology. The speed of sound depends on the helium abundance. Also solar models that give current L, M, and R require a certain initial helium abundance.
- Neon – x-ray and uv-spectroscopy of the solar corona. Measure relative to oxygen. Solar wind. Spectra of O and B stars
- Argon – solar wind relative to oxygen. Also theoretical interpolation between S and Ca based on nuclear equilibrium
- Krypton – infer from s-process systematics and solar wind
- Xenon – infer from s-process systematics and solar wind

Usually several uncertain methods are applied and consistency sought.

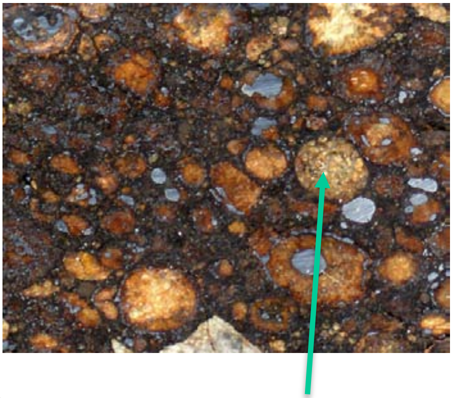
Meteorites

H. Schatz

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

But some gases escape and cannot be determined this way (for example hydrogen and the noble gases, and, to some extent CNO)

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.

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) .
Some, despite their names, have no chondrules.

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 only about 2% organic compounds, but 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 generally thought to be the most primitive because they contain water and organic material.


1969 Australia
~10 kg

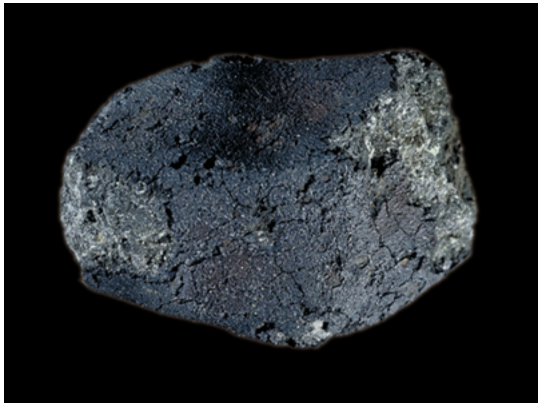
The CM meteorite Murchison, has over 70 extraterrestrial amino acids and other compounds including carboxylic acids, hydroxy carboxylic acids, sulphonic and phosphoric acids, aliphatic, aromatic, and polar hydrocarbons, fullerenes, heterocycles, carbonyl compounds, alcohols, amines, and amides.

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. CI carbonaceous chondrites lack the "condrules" that most other chondites have.

To understand the uncertainties involved in the determination of the various abundances read Palme et al (2014) paper and if you have time skim Asplund et al (2009) ARAA on the class website

The tables on the following pages summarize mostly Asplund et al's (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 type of) carbonaceous chondrite that fell in France in 1864. Over 13 kg of material was recovered from many fragments. It is by far the biggest CI-1 meteorite recovered.



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

68 out of 83 elements have been analyzed in the sun
(Lodders et al 2018)

In Asplund's list of *solar photospheric* abundances (neglecting Li and noble gases):

Very uncertain elements in the sun (0.3 > uncertainty > 0.2 dex)

boron, fluorine, chlorine, indium, thallium

Unseen in the sun (must take from meteorites)

Arsenic, selenium, bromine, technetium (Z = 43, unstable), cadmium, antimony, tellurium, iodine, cesium, tantalum, rhenium, platinum, mercury, bismuth, promethium (Z = 61, unstable), and all elements heavier than lead (Z = 82), except for thorium.

In meteorites

Where not affected by evaporation, most good to 0.04 dex except mercury (0.08 dex)

Palme et al (2014) Photosphere vs Meteoritic Abundances

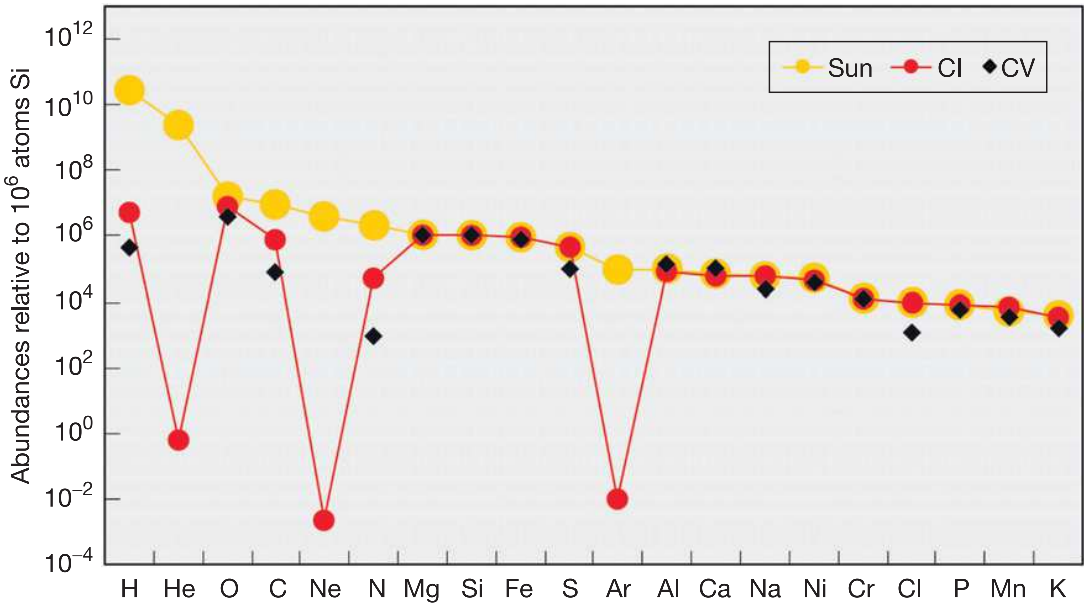


Figure 5 The abundances of the 20 most abundant elements in the Sun are compared with CI chondrite abundances. Rare gases show the largest depletion in Orgueil, followed by hydrogen, nitrogen, carbon, and oxygen. CV chondrites are also plotted. Their fit with solar abundances is worse than the fit with CI chondrites. A more detailed comparison between meteoritic and solar abundances is given in **Figure 6**.

From Asplund et al (2009,ARAA)

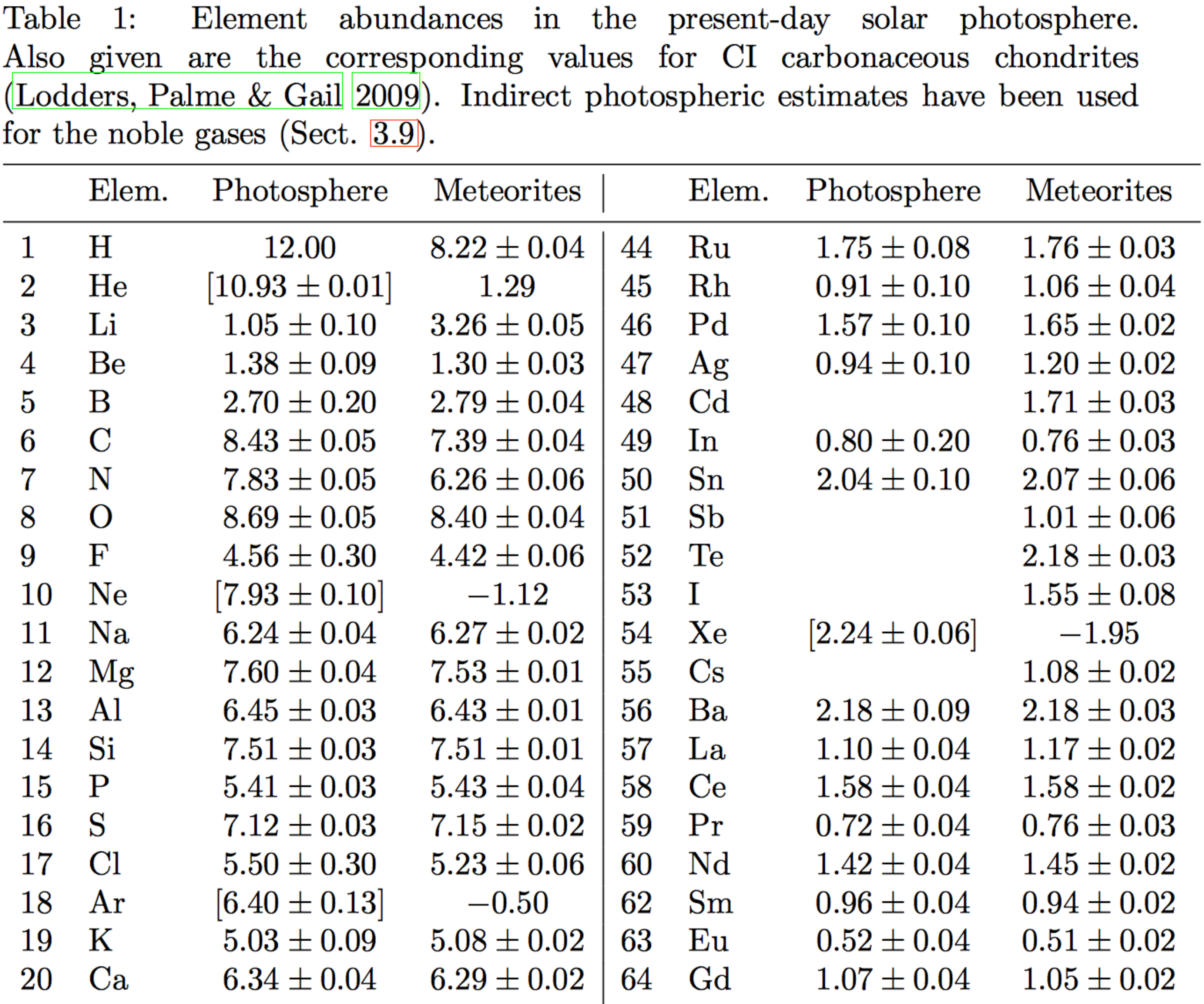


Table 1: Element abundances in the present-day solar photosphere. Also given are the corresponding values for CI carbonaceous chondrites (Lodders, Palme & Gail 2009). Indirect photospheric estimates have been used for the noble gases (Sect. 3.9).

	Elem.	Photosphere	Meteorites		Elem.	Photosphere	Meteorites
1	H	12.00	8.22 ± 0.04	44	Ru	1.75 ± 0.08	1.76 ± 0.03
2	He	$[10.93 \pm 0.01]$	1.29	45	Rh	0.91 ± 0.10	1.06 ± 0.04
3	Li	1.05 ± 0.10	3.26 ± 0.05	46	Pd	1.57 ± 0.10	1.65 ± 0.02
4	Be	1.38 ± 0.09	1.30 ± 0.03	47	Ag	0.94 ± 0.10	1.20 ± 0.02
5	B	2.70 ± 0.20	2.79 ± 0.04	48	Cd		1.71 ± 0.03
6	C	8.43 ± 0.05	7.39 ± 0.04	49	In	0.80 ± 0.20	0.76 ± 0.03
7	N	7.83 ± 0.05	6.26 ± 0.06	50	Sn	2.04 ± 0.10	2.07 ± 0.06
8	O	8.69 ± 0.05	8.40 ± 0.04	51	Sb		1.01 ± 0.06
9	F	4.56 ± 0.30	4.42 ± 0.06	52	Te		2.18 ± 0.03
10	Ne	$[7.93 \pm 0.10]$	-1.12	53	I		1.55 ± 0.08
11	Na	6.24 ± 0.04	6.27 ± 0.02	54	Xe	$[2.24 \pm 0.06]$	-1.95
12	Mg	7.60 ± 0.04	7.53 ± 0.01	55	Cs		1.08 ± 0.02
13	Al	6.45 ± 0.03	6.43 ± 0.01	56	Ba	2.18 ± 0.09	2.18 ± 0.03
14	Si	7.51 ± 0.03	7.51 ± 0.01	57	La	1.10 ± 0.04	1.17 ± 0.02
15	P	5.41 ± 0.03	5.43 ± 0.04	58	Ce	1.58 ± 0.04	1.58 ± 0.02
16	S	7.12 ± 0.03	7.15 ± 0.02	59	Pr	0.72 ± 0.04	0.76 ± 0.03
17	Cl	5.50 ± 0.30	5.23 ± 0.06	60	Nd	1.42 ± 0.04	1.45 ± 0.02
18	Ar	$[6.40 \pm 0.13]$	-0.50	62	Sm	0.96 ± 0.04	0.94 ± 0.02
19	K	5.03 ± 0.09	5.08 ± 0.02	63	Eu	0.52 ± 0.04	0.51 ± 0.02
20	Ca	6.34 ± 0.04	6.29 ± 0.02	64	Gd	1.07 ± 0.04	1.05 ± 0.02

20	Ca	6.34 ± 0.04	6.29 ± 0.02
21	Sc	3.15 ± 0.04	3.05 ± 0.02
22	Ti	4.95 ± 0.05	4.91 ± 0.03
23	V	3.93 ± 0.08	3.96 ± 0.02
24	Cr	5.64 ± 0.04	5.64 ± 0.01
25	Mn	5.43 ± 0.05	5.48 ± 0.01
26	Fe	7.50 ± 0.04	7.45 ± 0.01
27	Co	4.99 ± 0.07	4.87 ± 0.01
28	Ni	6.22 ± 0.04	6.20 ± 0.01
29	Cu	4.19 ± 0.04	4.25 ± 0.04
30	Zn	4.56 ± 0.05	4.63 ± 0.04
31	Ga	3.04 ± 0.09	3.08 ± 0.02
32	Ge	3.65 ± 0.10	3.58 ± 0.04
33	As		2.30 ± 0.04
34	Se		3.34 ± 0.03
35	Br		2.54 ± 0.06
36	Kr	[3.25 ± 0.06]	−2.27
37	Rb	2.52 ± 0.10	2.36 ± 0.03
38	Sr	2.87 ± 0.07	2.88 ± 0.03
39	Y	2.21 ± 0.05	2.17 ± 0.04
40	Zr	2.58 ± 0.04	2.53 ± 0.04
41	Nb	1.46 ± 0.04	1.41 ± 0.04
42	Mo	1.88 ± 0.08	1.94 ± 0.04
64	Gd	1.07 ± 0.04	1.05 ± 0.02
65	Tb	0.30 ± 0.10	0.32 ± 0.03
66	Dy	1.10 ± 0.04	1.13 ± 0.02
67	Ho	0.48 ± 0.11	0.47 ± 0.03
68	Er	0.92 ± 0.05	0.92 ± 0.02
69	Tm	0.10 ± 0.04	0.12 ± 0.03
70	Yb	0.84 ± 0.11	0.92 ± 0.02
71	Lu	0.10 ± 0.09	0.09 ± 0.02
72	Hf	0.85 ± 0.04	0.71 ± 0.02
73	Ta		-0.12 ± 0.04
74	W	0.85 ± 0.12	0.65 ± 0.04
75	Re		0.26 ± 0.04
76	Os	1.40 ± 0.08	1.35 ± 0.03
77	Ir	1.38 ± 0.07	1.32 ± 0.02
78	Pt		1.62 ± 0.03
79	Au	0.92 ± 0.10	0.80 ± 0.04
80	Hg		1.17 ± 0.08
81	Tl	0.90 ± 0.20	0.77 ± 0.03
82	Pb	1.75 ± 0.10	2.04 ± 0.03
83	Bi		0.65 ± 0.04
90	Th	0.02 ± 0.10	0.06 ± 0.03
92	U		-0.54 ± 0.03

Scanning the table one notes:

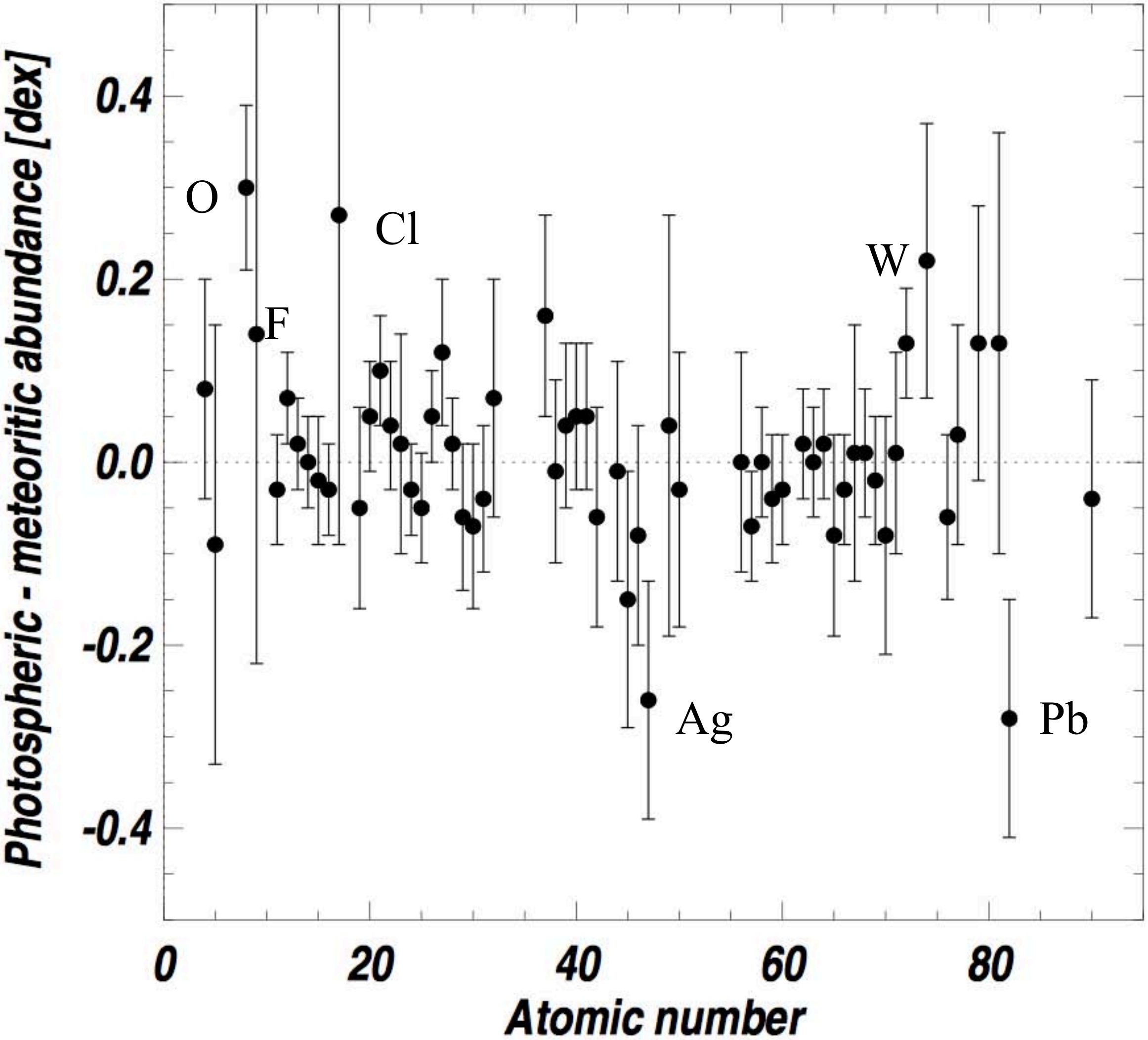
a) H and He have escaped from the meteorites

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

c) C, N, and to a lesser extent O, are also depleted in the meteorites

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

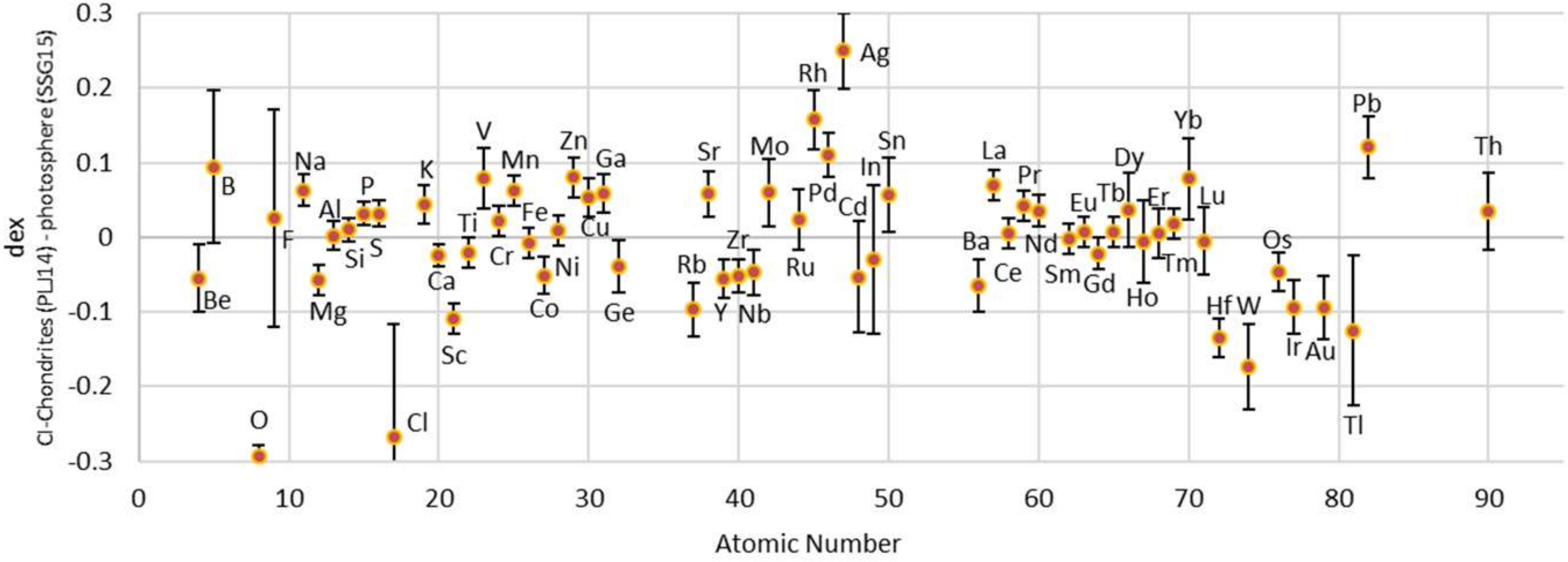
e) Agreement is pretty good for the rest – where the element has been measured in both the sun and meteorites



Asplund et al
(2009; ARAA)

Figure 7: Difference between the logarithmic abundances determined from the solar photosphere and the CI carbonaceous chondrites as a function of atomic number. With a few exceptions the agreement is excellent. Note that due to depletion in the Sun and meteorites, the data points for Li, C, N and the noble gases fall outside the range of the figure.

Lodders (2018) meteoritic and photospheric abundances compared. CNO and noble gasses and Li are off scale.



Asplund et al (2009 ARAA)

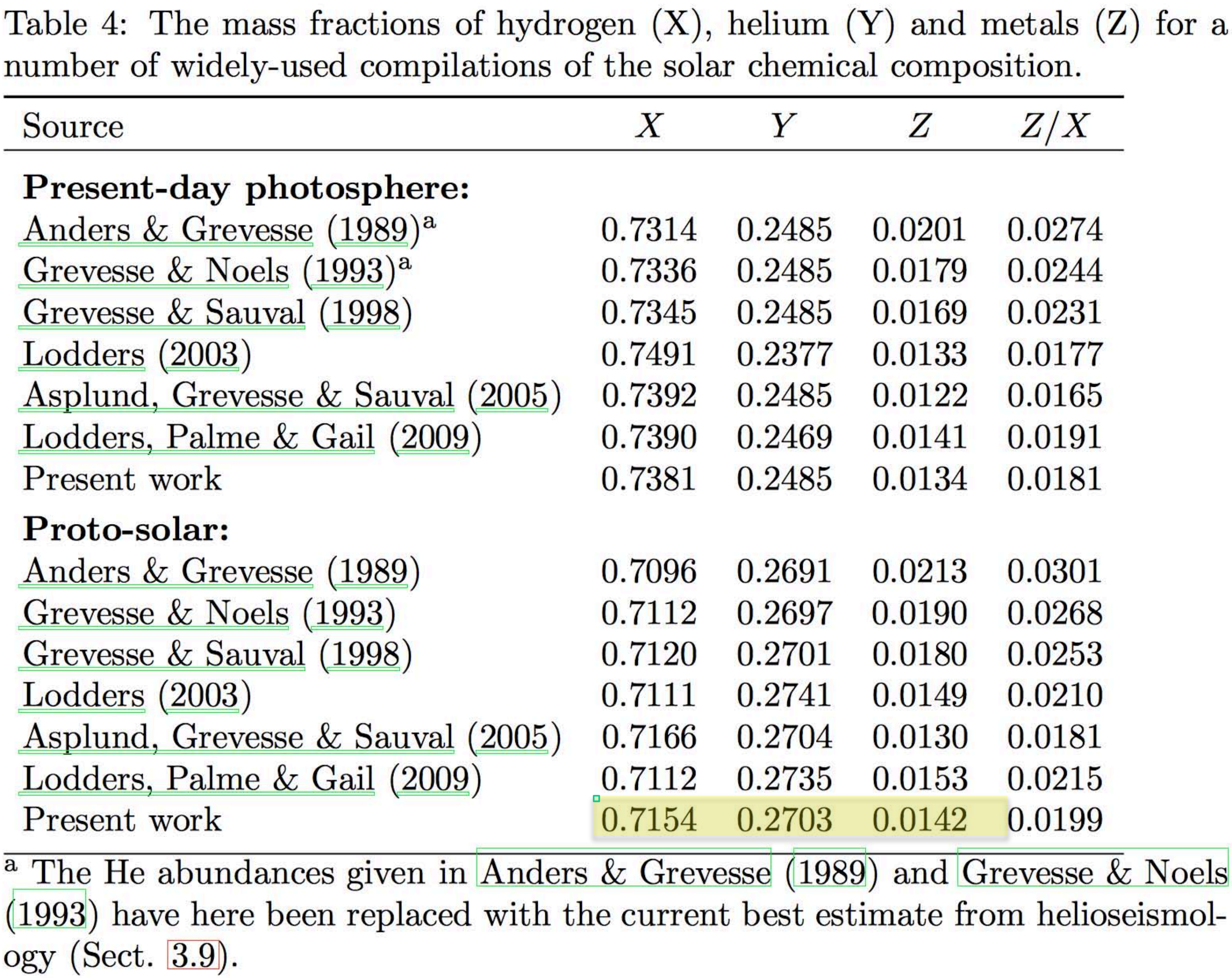


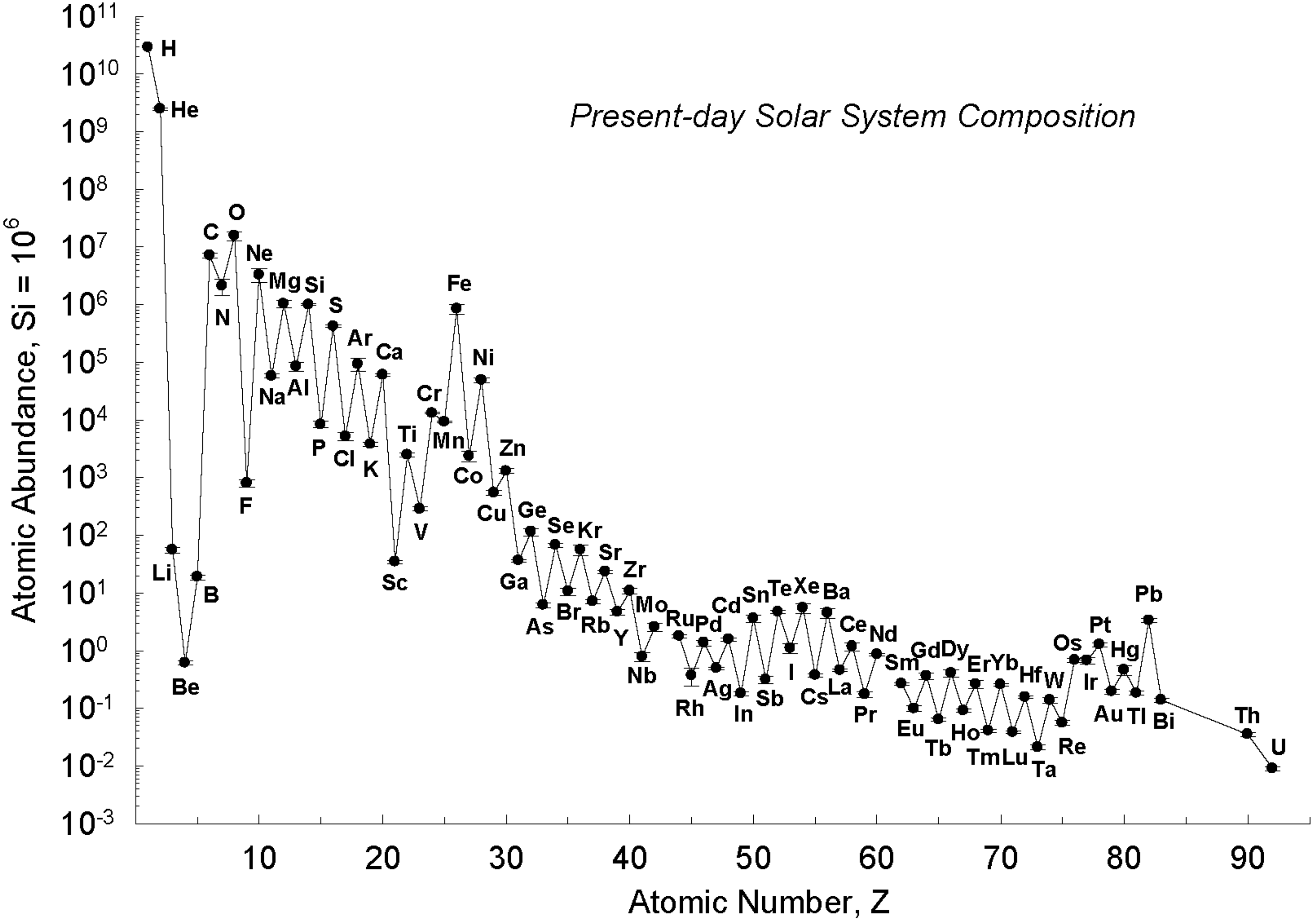
Table 4: The mass fractions of hydrogen (X), helium (Y) and metals (Z) for a number of widely-used compilations of the solar chemical composition.

Source	X	Y	Z	Z/X
Present-day photosphere:				
Anders & Grevesse (1989)[a]	0.7314	0.2485	0.0201	0.0274
Grevesse & Noels (1993)[a]	0.7336	0.2485	0.0179	0.0244
Grevesse & Sauval (1998)	0.7345	0.2485	0.0169	0.0231
Lodders (2003)	0.7491	0.2377	0.0133	0.0177
Asplund, Grevesse & Sauval (2005)	0.7392	0.2485	0.0122	0.0165
Lodders, Palme & Gail (2009)	0.7390	0.2469	0.0141	0.0191
Present work	0.7381	0.2485	0.0134	0.0181
Proto-solar:				
Anders & Grevesse (1989)	0.7096	0.2691	0.0213	0.0301
Grevesse & Noels (1993)	0.7112	0.2697	0.0190	0.0268
Grevesse & Sauval (1998)	0.7120	0.2701	0.0180	0.0253
Lodders (2003)	0.7111	0.2741	0.0149	0.0210
Asplund, Grevesse & Sauval (2005)	0.7166	0.2704	0.0130	0.0181
Lodders, Palme & Gail (2009)	0.7112	0.2735	0.0153	0.0215
Present work	0.7154	0.2703	0.0142	0.0199

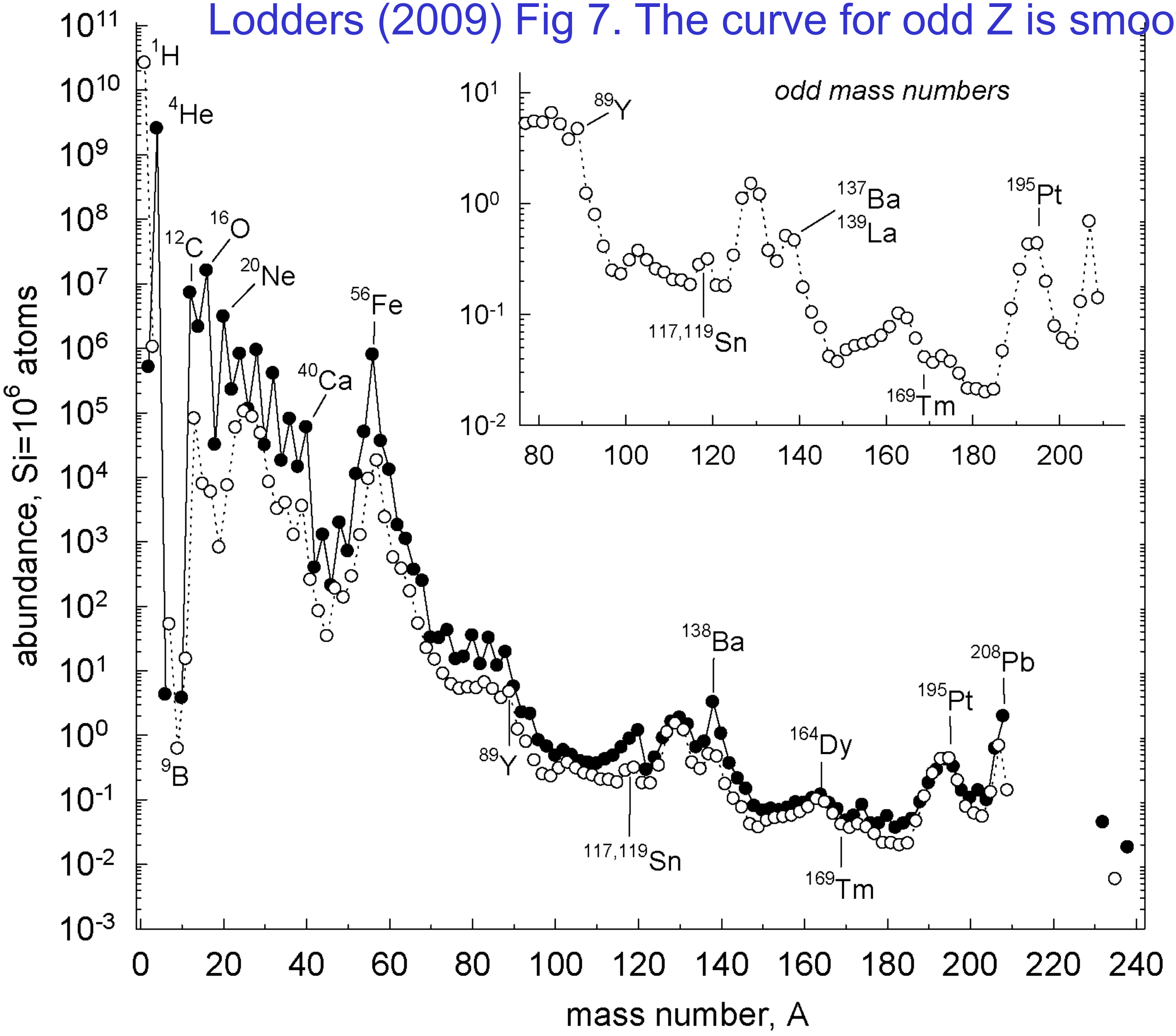
---

[a] The He abundances given in Anders & Grevesse (1989) and Grevesse & Noels (1993) have here been replaced with the current best estimate from helioseismology (Sect. 3.9).

- see Turcotte and Winner-Schweingruber 2002, on class website/papers.)


Present-day Solar System Composition
Atomic Abundance, Si = 10^6
Atomic Number, Z
10^{11}
10^{10}
10^9
10^8
10^7
10^6
10^5
10^4
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10
20
30
40
50
60
70
80
90
H
He
Li
Be
B
C
N
O
F
Ne
Na
Mg
Al
Si
P
S
Cl
Ar
K
Ca
Sc
Ti
V
Cr
Mn
Fe
Co
Ni
Cu
Zn
Ga
Ge
As
Se
Br
Kr
Rb
Sr
Y
Zr
Nb
Mo
Ru
Rh
Pd
Ag
Cd
In
Sn
Sb
Te
I
Xe
Cs
Ba
La
Ce
Pr
Nd
Sm
Eu
Gd
Tb
Dy
Ho
Er
Tm
Yb
Lu
Hf
Ta
W
Re
Os
Ir
Pt
Au
Hg
Tl
Pb
Bi
Th
U

Isotopes with even and odd A plotted separately
Lodders (2009) Fig 7. The curve for odd Z is smoother.



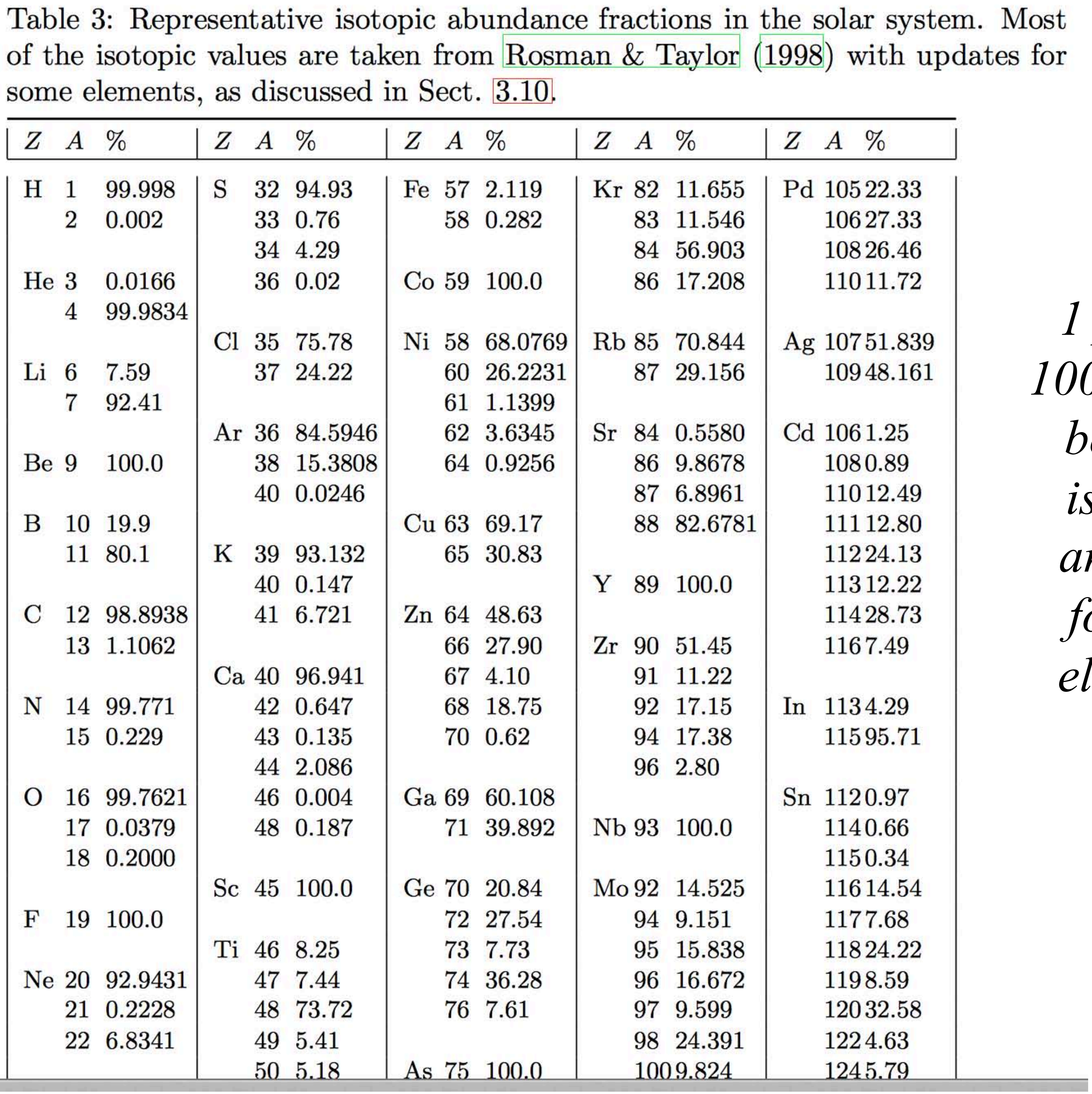


Table 3: Representative isotopic abundance fractions in the solar system. Most of the isotopic values are taken from Rosman & Taylor (1998) with updates for some elements, as discussed in Sect. 3.10.

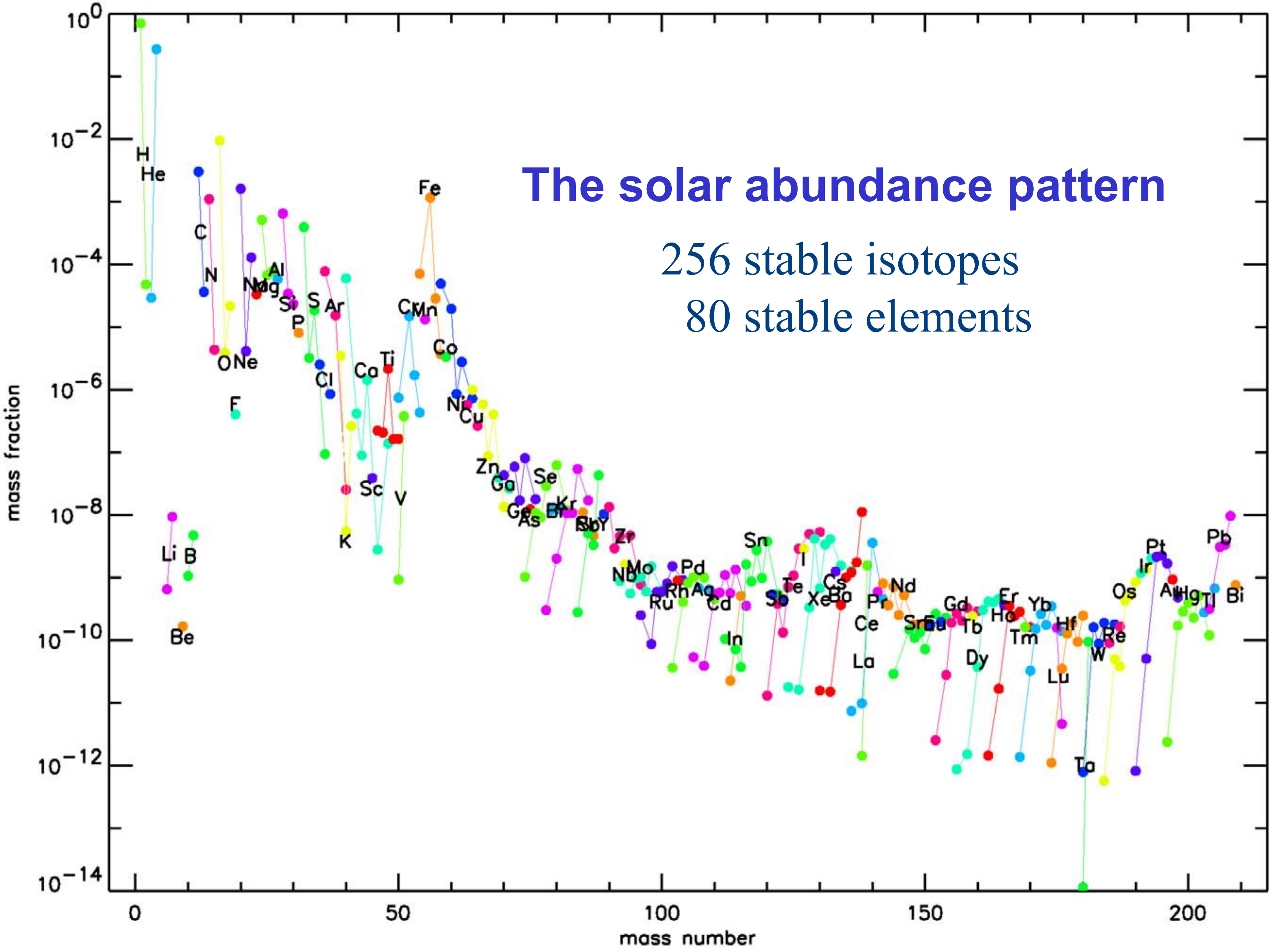
Z	A	%	Z	A	%	Z	A	%	Z	A	%	Z	A	%
H	1	99.998	S	32	94.93	Fe	57	2.119	Kr	82	11.655	Pd	105	22.33
	2	0.002		33	0.76		58	0.282		83	11.546		106	27.33
				34	4.29					84	56.903		108	26.46
He	3	0.0166		36	0.02	Co	59	100.0		86	17.208		110	11.72
	4	99.9834												
			Cl	35	75.78	Ni	58	68.0769	Rb	85	70.844	Ag	107	51.839
Li	6	7.59		37	24.22		60	26.2231		87	29.156		109	48.161
	7	92.41					61	1.1399						
			Ar	36	84.5946		62	3.6345	Sr	84	0.5580	Cd	106	1.25
Be	9	100.0		38	15.3808		64	0.9256		86	9.8678		108	0.89
				40	0.0246					87	6.8961		110	12.49
B	10	19.9				Cu	63	69.17		88	82.6781		111	12.80
	11	80.1	K	39	93.132		65	30.83					112	24.13
				40	0.147				Y	89	100.0		113	12.22
C	12	98.8938		41	6.721	Zn	64	48.63					114	28.73
	13	1.1062					66	27.90	Zr	90	51.45		116	7.49
			Ca	40	96.941		67	4.10		91	11.22			
N	14	99.771		42	0.647		68	18.75		92	17.15	In	113	4.29
	15	0.229		43	0.135		70	0.62		94	17.38		115	95.71
				44	2.086					96	2.80			
O	16	99.7621		46	0.004	Ga	69	60.108				Sn	112	0.97
	17	0.0379		48	0.187		71	39.892	Nb	93	100.0		114	0.66
	18	0.2000											115	0.34
			Sc	45	100.0	Ge	70	20.84	Mo	92	14.525		116	14.54
F	19	100.0					72	27.54		94	9.151		117	7.68
			Ti	46	8.25		73	7.73		95	15.838		118	24.22
Ne	20	92.9431		47	7.44		74	36.28		96	16.672		119	8.59
	21	0.2228		48	73.72		76	7.61		97	9.599		120	32.58
	22	6.8341		49	5.41					98	24.391		122	4.63
				50	5.18	As	75	100.0		100	9.824		124	5.79

1 part in 1000 would be a big isotopic anomaly for most elements.

Lodders (2009) translated into mass fractions – see class website for more

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

Etc.



The solar abundance pattern

256 stable isotopes

80 stable elements

Inferences from Solar Abundances

- H and He are from the Big Bang. Since the Big Bang H has declined somewhat (from 0.751 to 0.715) and He increased somewhat (from 0.249 to 0.270) due to stellar evolution (Brian Fields et al 2002)

- Deuterium and ^{3}He are very rare reflecting the ease with which they are destroyed in the presence of hot hydrogen

- There are no stable nuclei with $A = N+Z = 5$ or 8

- Li, Be, and B are also easily destroyed by hot hydrogen. Be and ^{10}B are thought to be produced by cosmic ray spallation of carbon in the ISM, a very inefficient process. Li has several origins.

- The abundant species up to Ca have neutron number (N) = proton number (Z). The most abundant ones, except for nitrogen have even Z, i.e., they are an integer number of alpha-particles (helium nuclei).

Inferences from Abundances

- Above Ca (Z=N=20), elements with even Z continue to be more abundant, but with a neutron excess – N > Z (e.g. ^{56}Fe Z = 26, N = 30)

- There is a big peak of abundances centered around iron with a rapid fall off above

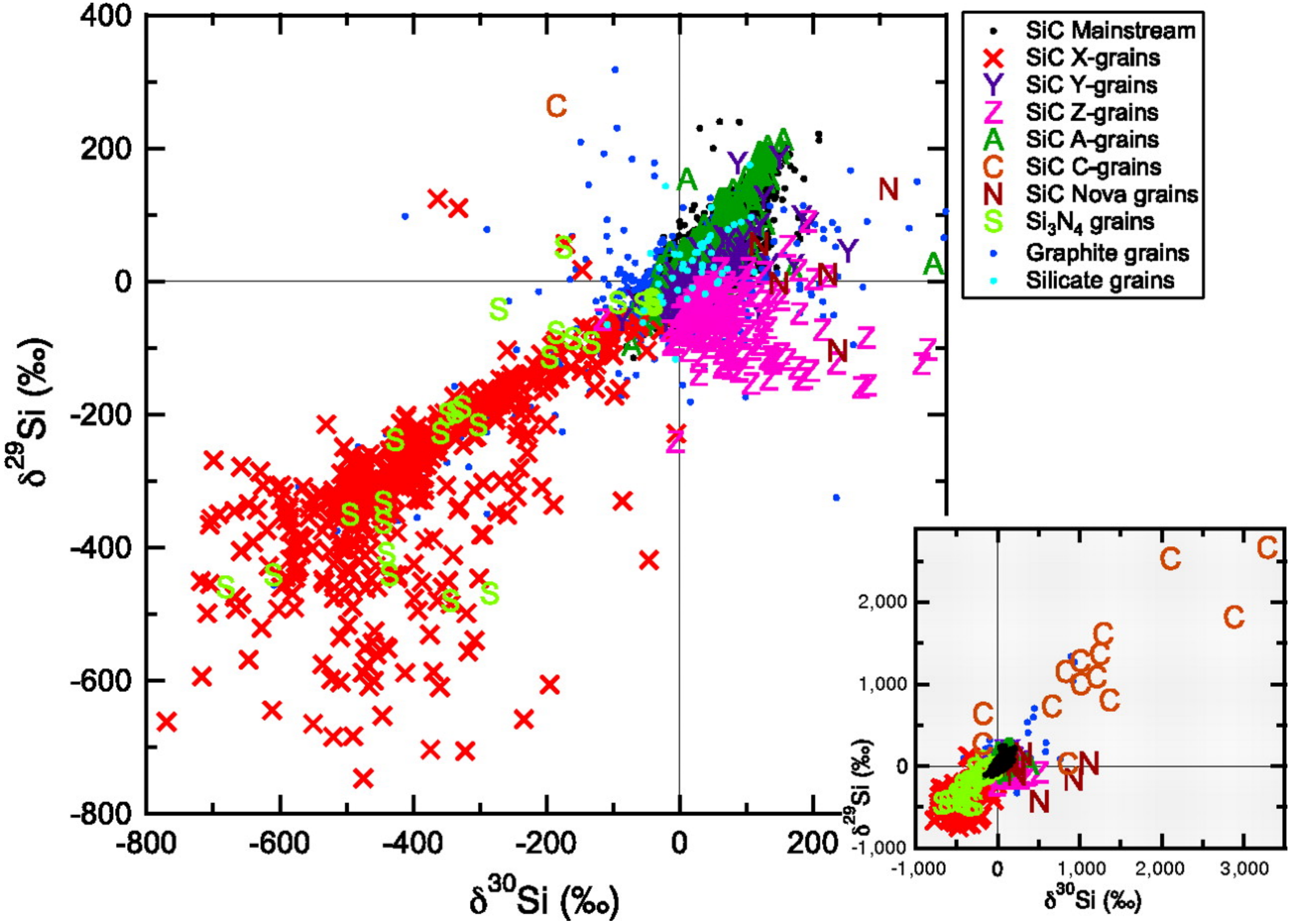
- For the elements heavier than iron, and to a lesser extent those lighter, isotopes with odd neutron number are less abundant than those with even neutron number and odd Z elements are less abundant

- There are also abundance peaks in the vicinity of A = 80, 130, 160, 195, and 208.

As we shall see all these properties reflect the inherent properties of the nucleus and to at least as much as the environments where the elements have been assembled. It may not be too surprising then to see that large pieces of this pattern are somewhat universal, i.e., not just a characteristic of the sun.

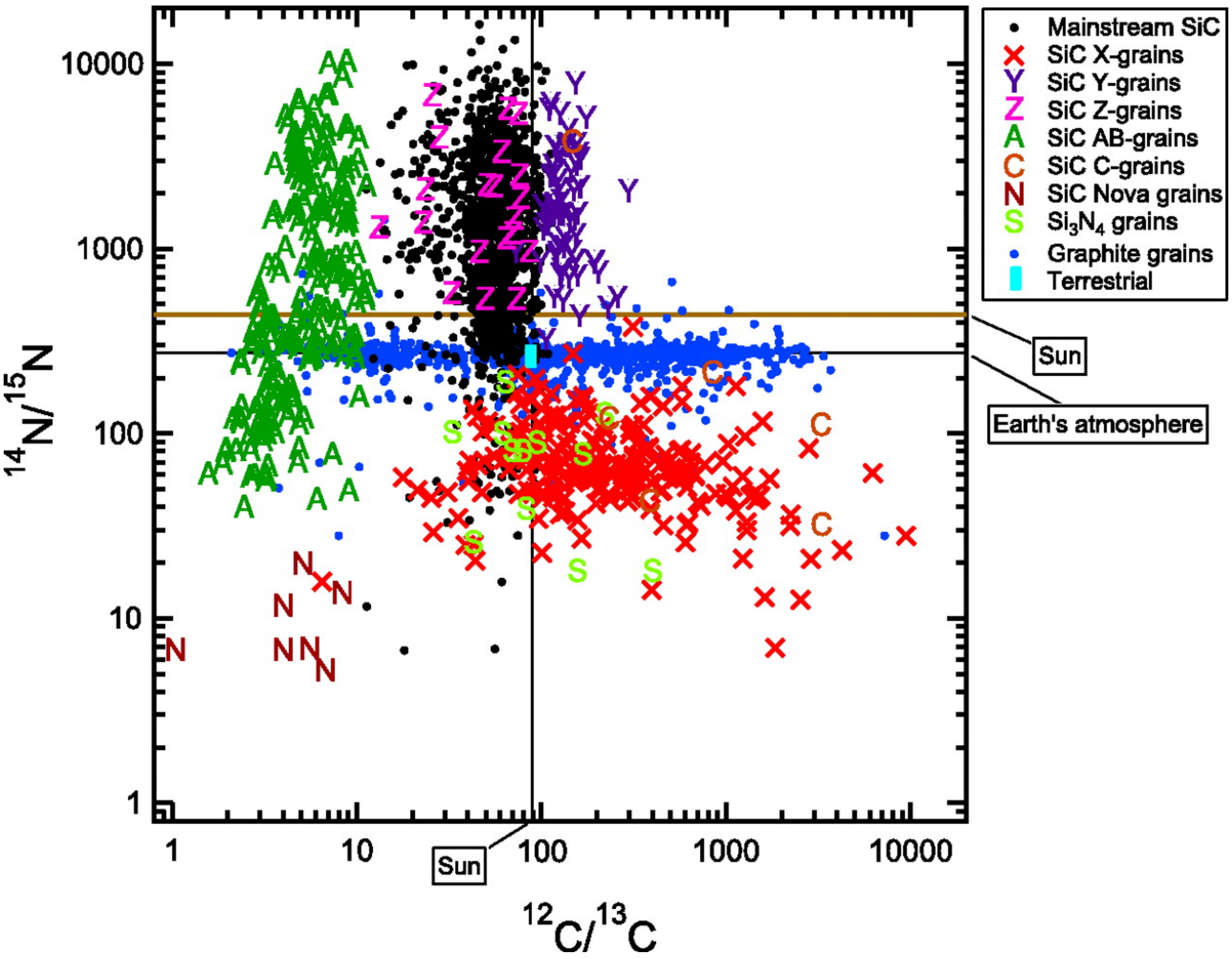
ISOTOPIC ANOMALIES IN METEORITES

Silicon isotopic compositions of presolar SiC, graphite, and silicates.



Andrew M. Davis PNAS 2011;108:48:19142-19146

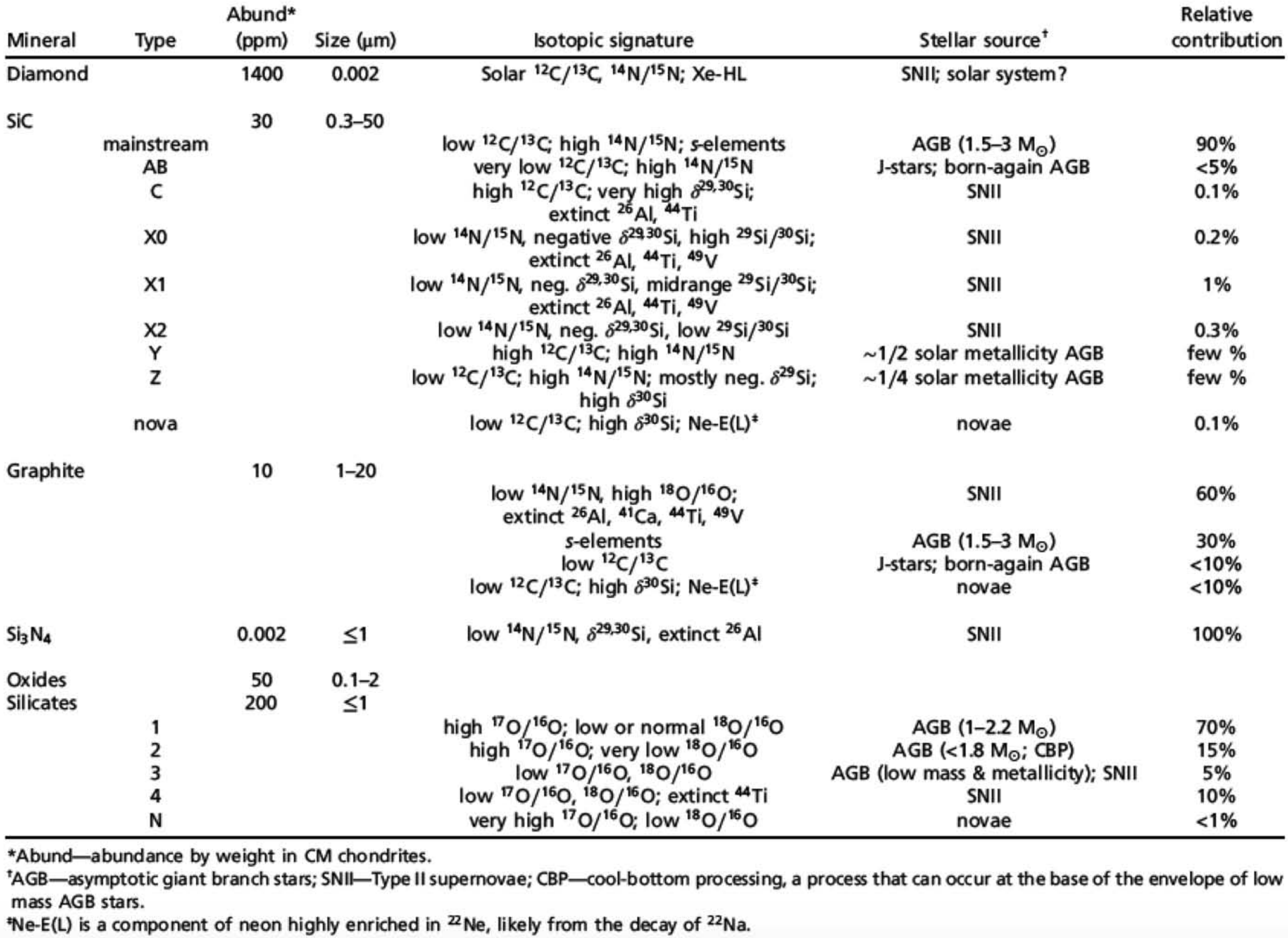
Carbon and nitrogen isotopic compositions of presolar SiC, graphite, and Si3N4.



Andrew M. Davis PNAS 2011;108:48:19142-19146

Davis (2011)

Table 1. Types, abundances, sizes, and sources of stardust (after 33,40)



Mineral	Type	Abund* (ppm)	Size (μm)	Isotopic signature	Stellar source†	Relative contribution
Diamond		1400	0.002	Solar $^{12}C/^{13}C$, $^{14}N/^{15}N$; Xe-HL	SNII; solar system?	
SiC		30	0.3–50			
	mainstream			low $^{12}C/^{13}C$; high $^{14}N/^{15}N$; *s*-elements	AGB (1.5–3 $M_\odot$)	90%
	AB			very low $^{12}C/^{13}C$; high $^{14}N/^{15}N$	J-stars; born-again AGB	<5%
	C			high $^{12}C/^{13}C$; very high $\delta^{29,30}Si$; extinct ^{26}Al, ^{44}Ti	SNII	0.1%
	X0			low $^{14}N/^{15}N$, negative $\delta^{29,30}Si$, high $^{29}Si/^{30}Si$; extinct ^{26}Al, ^{44}Ti, ^{49}V	SNII	0.2%
	X1			low $^{14}N/^{15}N$, neg. $\delta^{29,30}Si$, midrange $^{29}Si/^{30}Si$; extinct ^{26}Al, ^{44}Ti, ^{49}V	SNII	1%
	X2			low $^{14}N/^{15}N$, neg. $\delta^{29,30}Si$, low $^{29}Si/^{30}Si$	SNII	0.3%
	Y			high $^{12}C/^{13}C$; high $^{14}N/^{15}N$	~1/2 solar metallicity AGB	few %
	Z			low $^{12}C/^{13}C$; high $^{14}N/^{15}N$; mostly neg. $\delta^{29}Si$; high $\delta^{30}Si$	~1/4 solar metallicity AGB	few %
	nova			low $^{12}C/^{13}C$; high $\delta^{30}Si$; Ne-E(L)‡	novae	0.1%
Graphite		10	1–20			
				low $^{14}N/^{15}N$, high $^{18}O/^{16}O$; extinct ^{26}Al, ^{41}Ca, ^{44}Ti, ^{49}V	SNII	60%
				s-elements	AGB (1.5–3 $M_\odot$)	30%
				low $^{12}C/^{13}C$	J-stars; born-again AGB	<10%
				low $^{12}C/^{13}C$; high $\delta^{30}Si$; Ne-E(L)‡	novae	<10%
Si_3N_4		0.002	≤1	low $^{14}N/^{15}N$, $\delta^{29,30}Si$, extinct ^{26}Al	SNII	100%
Oxides		50	0.1–2			
Silicates		200	≤1			
	1			high $^{17}O/^{16}O$; low or normal $^{18}O/^{16}O$	AGB (1–2.2 $M_\odot$)	70%
	2			high $^{17}O/^{16}O$; very low $^{18}O/^{16}O$	AGB (<1.8 $M_\odot$; CBP)	15%
	3			low $^{17}O/^{16}O$, $^{18}O/^{16}O$	AGB (low mass & metallicity); SNII	5%
	4			low $^{17}O/^{16}O$, $^{18}O/^{16}O$; extinct ^{44}Ti	SNII	10%
	N			very high $^{17}O/^{16}O$; low $^{18}O/^{16}O$	novae	<1%

*Abund—abundance by weight in CM chondrites.

†AGB—asymptotic giant branch stars; SNII—Type II supernovae; CBP—cool-bottom processing, a process that can occur at the base of the envelope of low mass AGB stars.

‡Ne-E(L) is a component of neon highly enriched in ^{22}Ne, likely from the decay of ^{22}Na.

Presolar grains often show the effects of decay of extinct radionuclides. Among the short-lived radionuclides whose presence has been inferred are ^{26}Al ($T_{1/2} = 7.1 \times 10^5$ y), ^{41}Ca ($T_{1/2} = 1.03 \times 10^5$ y), ^{44}Ti ($T_{1/2} = 59$ y), ^{49}V ($T_{1/2} = 331$ d), ^{93}Zr ($T_{1/2} = 1.5 \times 10^6$ y), ^{99}Tc ($T_{1/2} = 2.13 \times 10^5$ y), and ^{135}Cs ($T_{1/2} = 2.3 \times 10^6$ y).

The inferred presence of ^{49}V in supernova SiC grains is particularly interesting, as it implies grain condensation within a couple of years of the explosion, but is also equivocal. Early condensation of dust has been observed around supernova 1987A, but the ^{49}Ti excesses used to infer the presence of ^{49}V in presolar grains may have other origins within supernovae.

Other abundances outside the solar neighborhood ?

- 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

Asplund et al (2009)

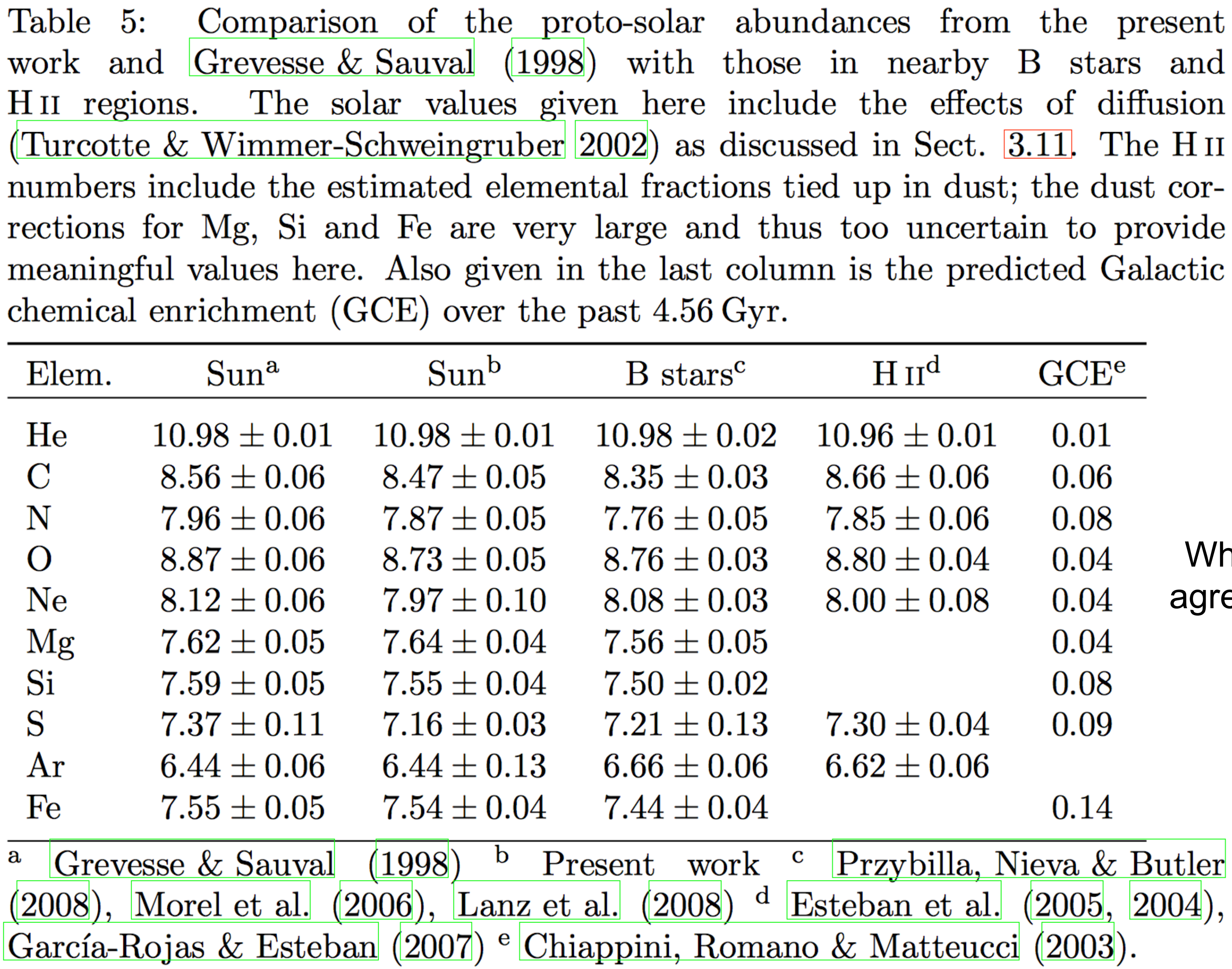


Table 5: Comparison of the proto-solar abundances from the present work and Grevesse & Sauval (1998) with those in nearby B stars and H II regions. The solar values given here include the effects of diffusion (Turcotte & Wimmer-Schweingruber 2002) as discussed in Sect. 3.11. The H II numbers include the estimated elemental fractions tied up in dust; the dust corrections for Mg, Si and Fe are very large and thus too uncertain to provide meaningful values here. Also given in the last column is the predicted Galactic chemical enrichment (GCE) over the past 4.56 Gyr.

Elem.	Sun[a]	Sun[b]	B stars[c]	H II[d]	GCE[e]
He	10.98 ± 0.01	10.98 ± 0.01	10.98 ± 0.02	10.96 ± 0.01	0.01
C	8.56 ± 0.06	8.47 ± 0.05	8.35 ± 0.03	8.66 ± 0.06	0.06
N	7.96 ± 0.06	7.87 ± 0.05	7.76 ± 0.05	7.85 ± 0.06	0.08
O	8.87 ± 0.06	8.73 ± 0.05	8.76 ± 0.03	8.80 ± 0.04	0.04
Ne	8.12 ± 0.06	7.97 ± 0.10	8.08 ± 0.03	8.00 ± 0.08	0.04
Mg	7.62 ± 0.05	7.64 ± 0.04	7.56 ± 0.05		0.04
Si	7.59 ± 0.05	7.55 ± 0.04	7.50 ± 0.02		0.08
S	7.37 ± 0.11	7.16 ± 0.03	7.21 ± 0.13	7.30 ± 0.04	0.09
Ar	6.44 ± 0.06	6.44 ± 0.13	6.66 ± 0.06	6.62 ± 0.06	
Fe	7.55 ± 0.05	7.54 ± 0.04	7.44 ± 0.04		0.14

[a] Grevesse & Sauval (1998) [b] Present work [c] Przybilla, Nieva & Butler (2008), Morel et al. (2006), Lanz et al. (2008) [d] Esteban et al. (2005, 2004), García-Rojas & Esteban (2007) [e] Chiappini, Romano & Matteucci (2003).

Why do they agree so well?

[b] Metals increased by 0.04 dex to account for diffusion

Dust complicates measurements in the ISM

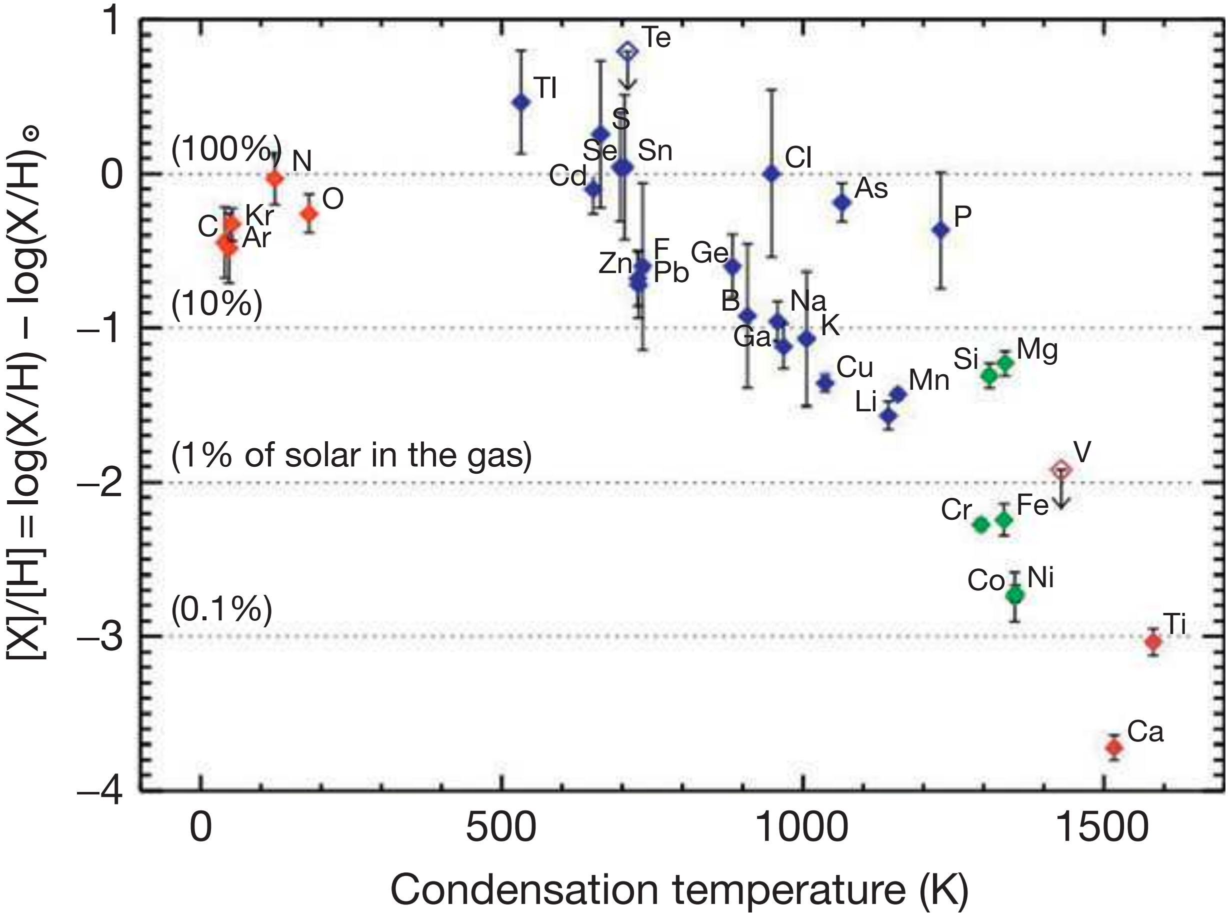
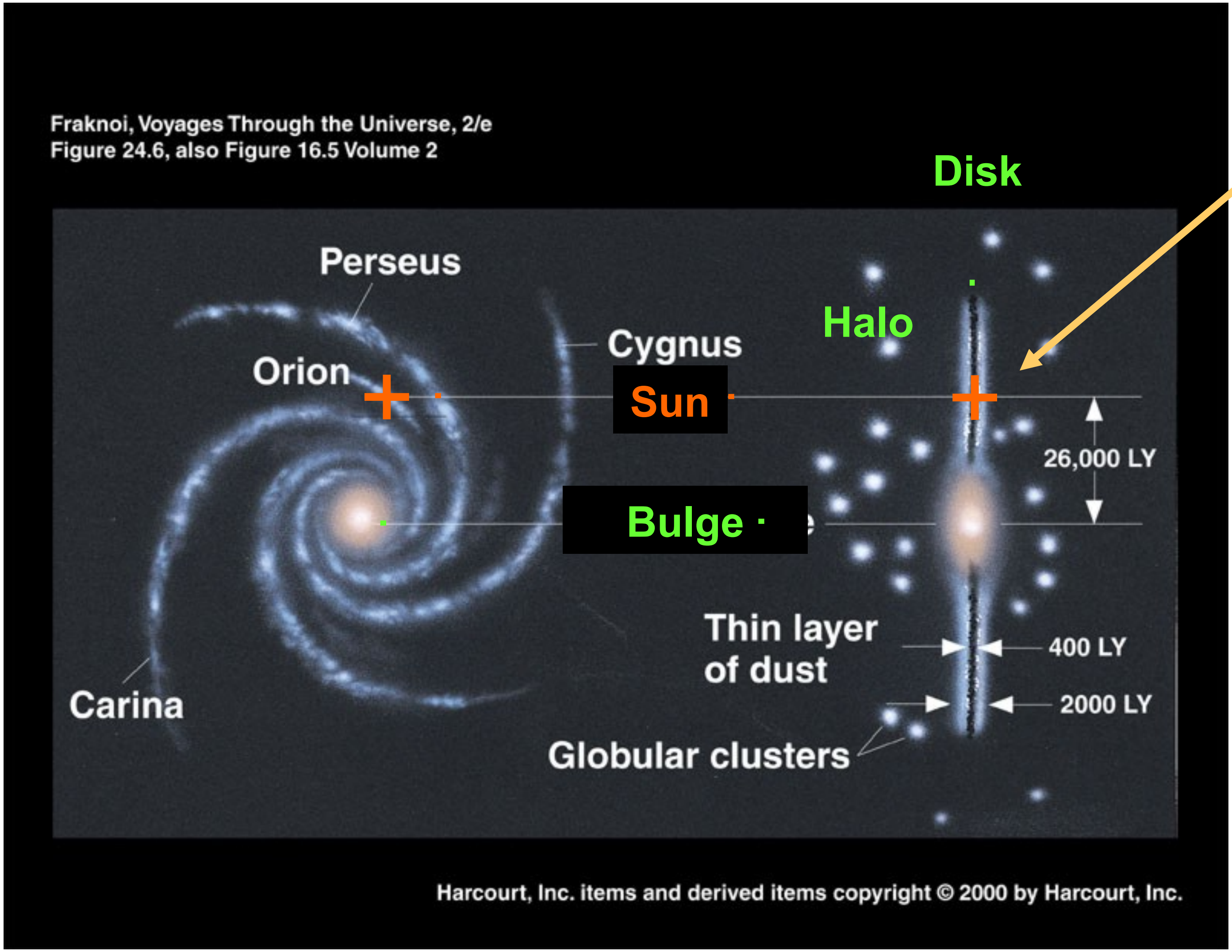


Figure 9 Abundances of the elements along the line of sight toward ζ Oph (ζ Ophiuchus), a moderately reddened star that is frequently used as standard for depletion studies. The ratios of ζ Oph abundances to the

Palme et al (2014)

The solar abundance distribution - should reflect the composition of the ISM when and where the sun was born

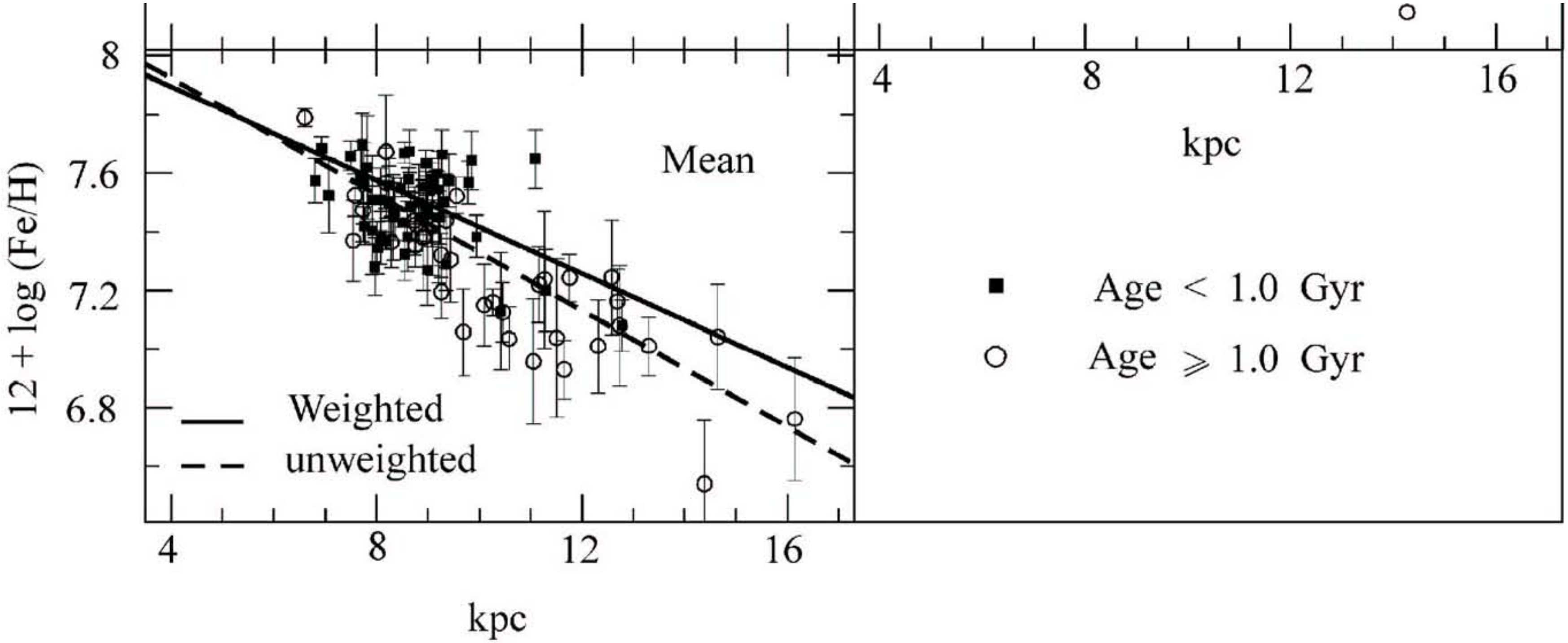


Fraknoi, Voyages Through the Universe, 2/e
Figure 24.6, also Figure 16.5 Volume 2

solar abundances:

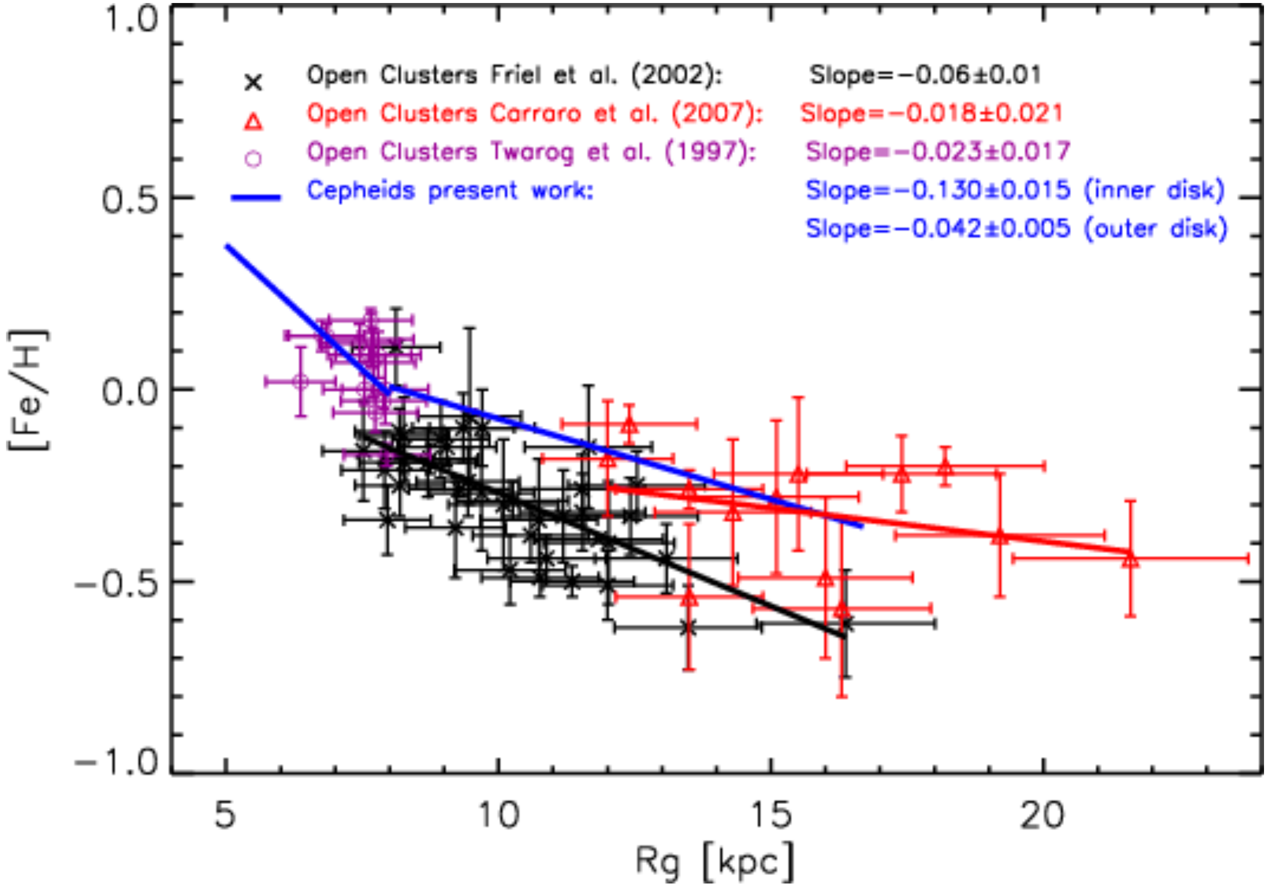
Elemental (and isotopic) composition of Galaxy at location of solar system at the time of it's formation

Observed metallicity gradient in Galactic disk:



Many other works on this subject
See e.g. Luck et al, 132, 902, AJ (2006)
radial Fe gradient = - 0.068 +_ 0.003 dex/kpc
from 54 Cepheids

Hou et al. Chin. J. Astron. Astrophys. 2 (2002)
data from 89 open clusters
radial iron gradient = -0.099 +_ 0.008 dex/kpc



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.

From Luck et al.

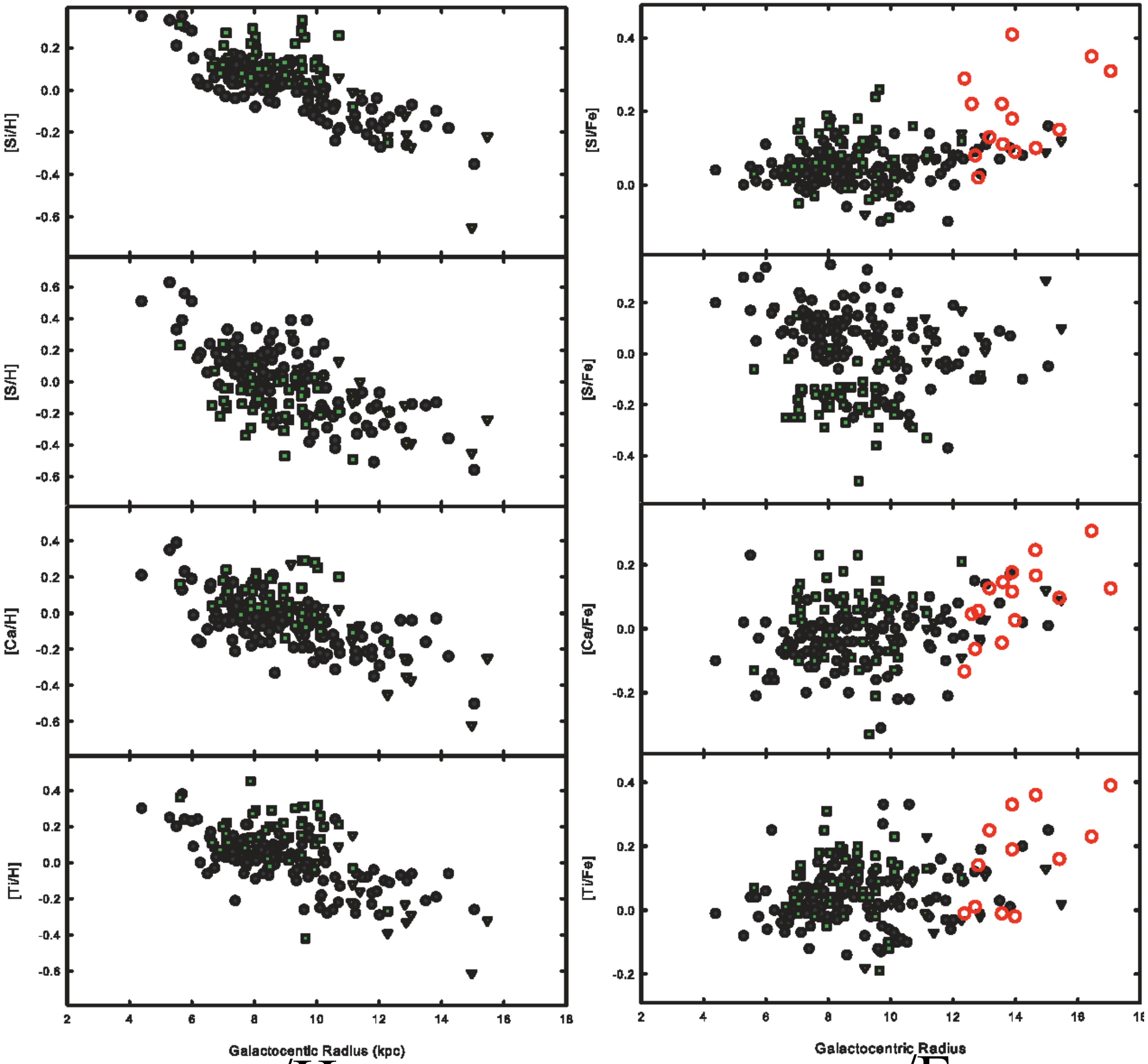
Abundance Patterns with Radius

Si

S

Ca

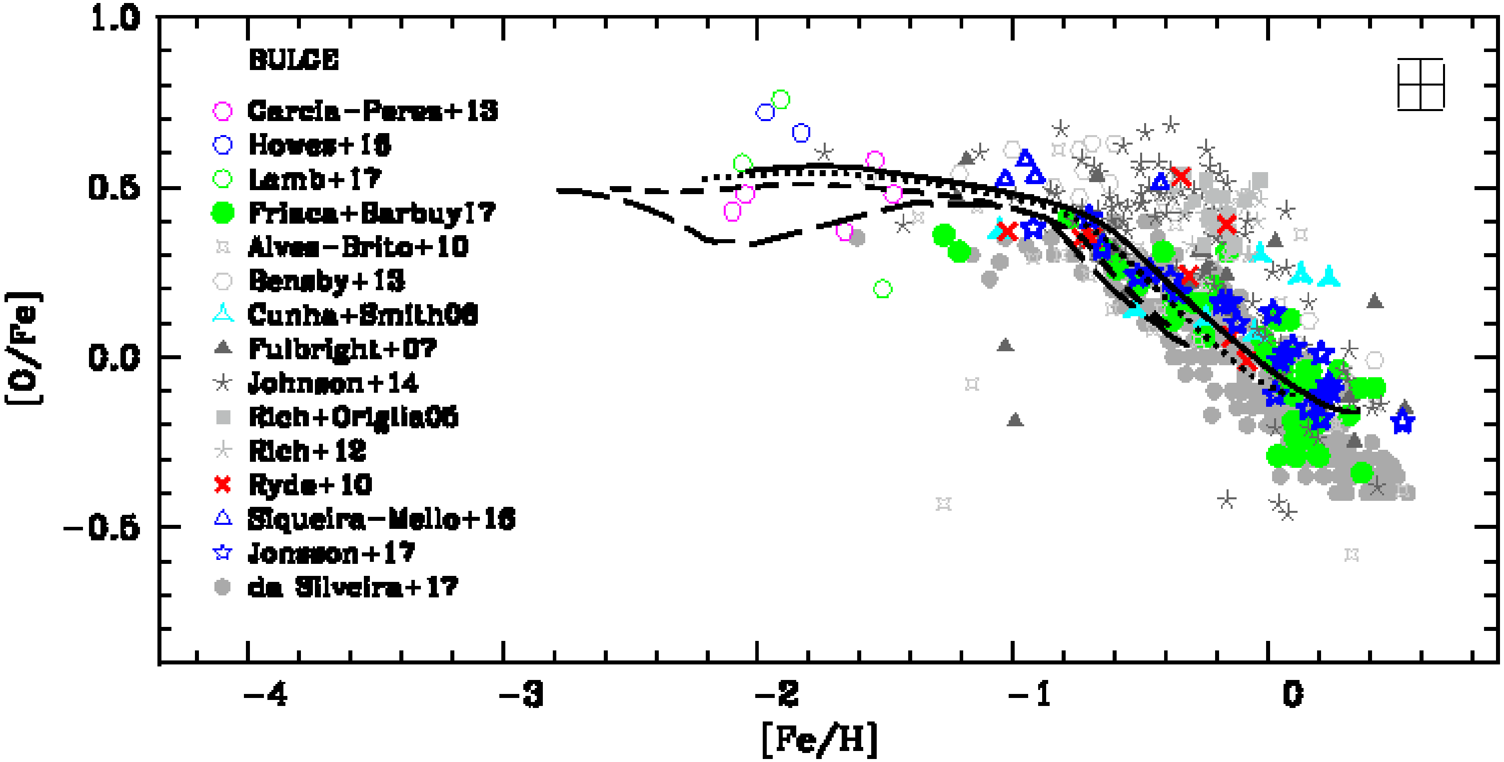
Ti



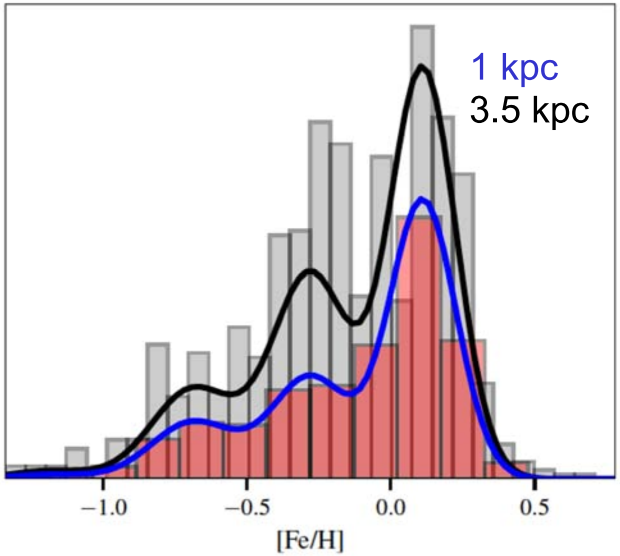
/H

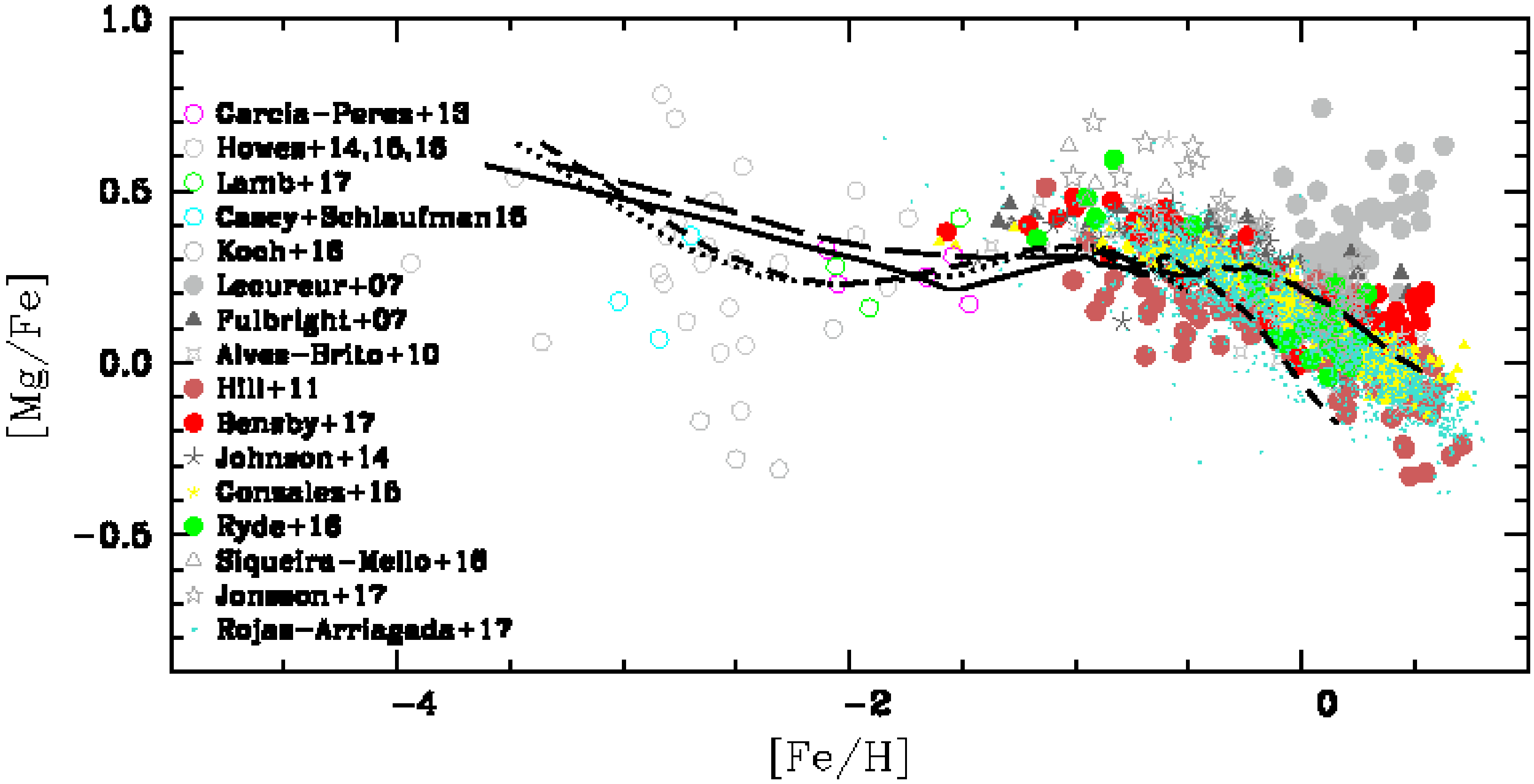
/Fe

Galactic Bulge

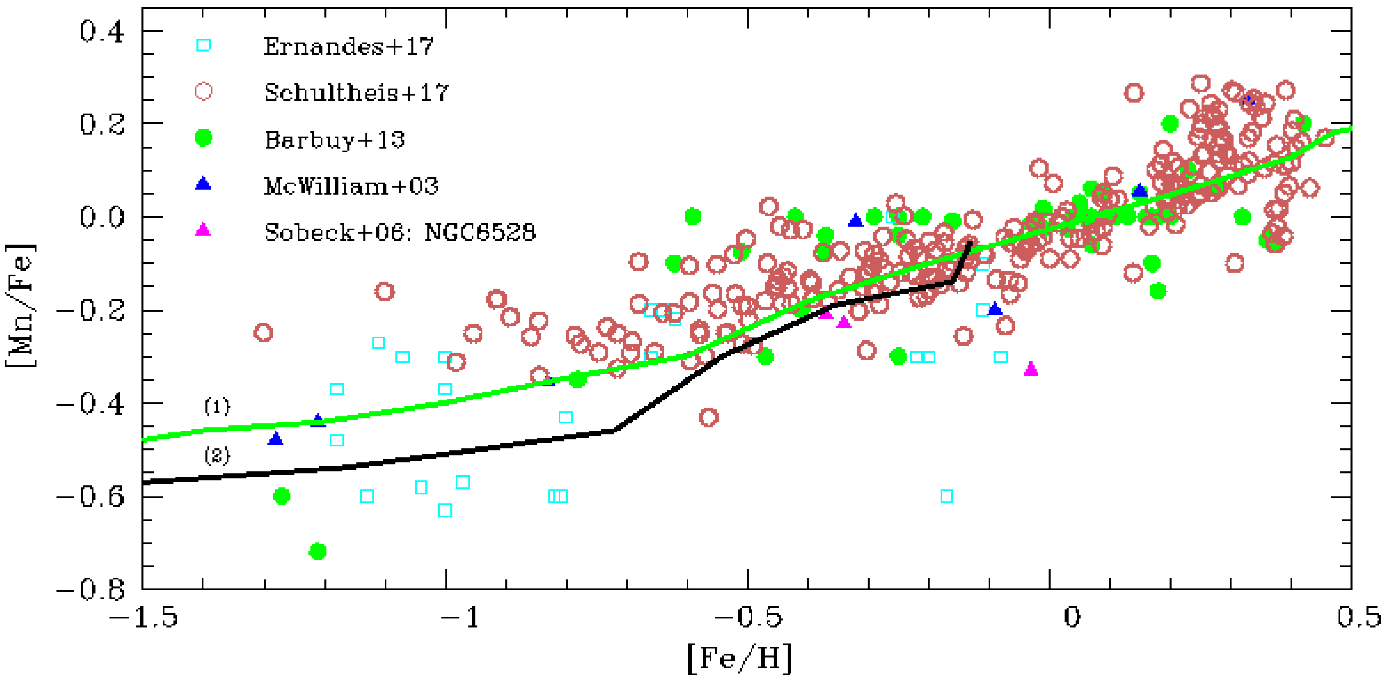


Barbuy et al (2018, ARAA) abundances for Galactic Bulge stars. Geochemical evolutionary models are plotted as lines. Solid line: r<0.5 kpc; dotted line: 0.5<r<1 kpc; dashed lines: 1<r<2 kpc; long-dashed lines: 2<r<3 kpc.

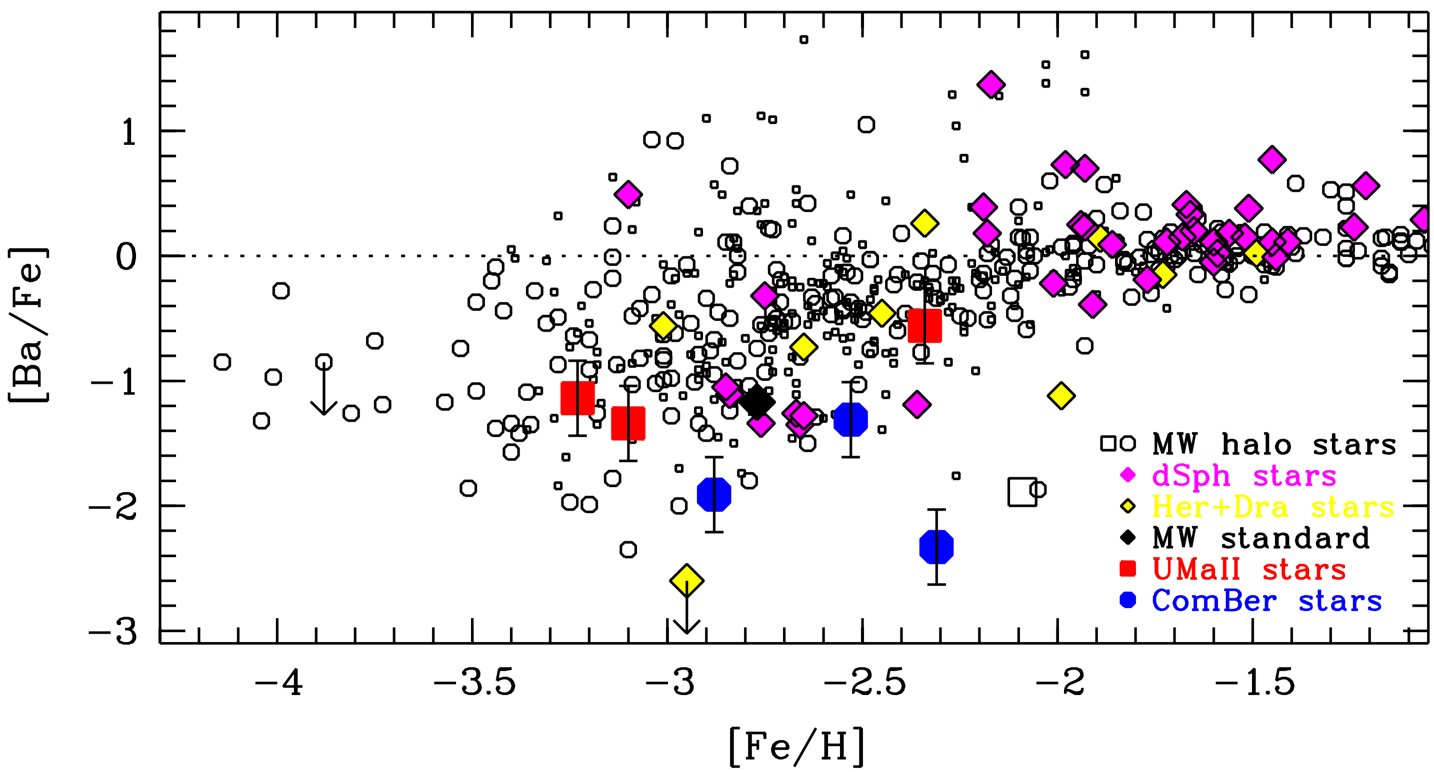




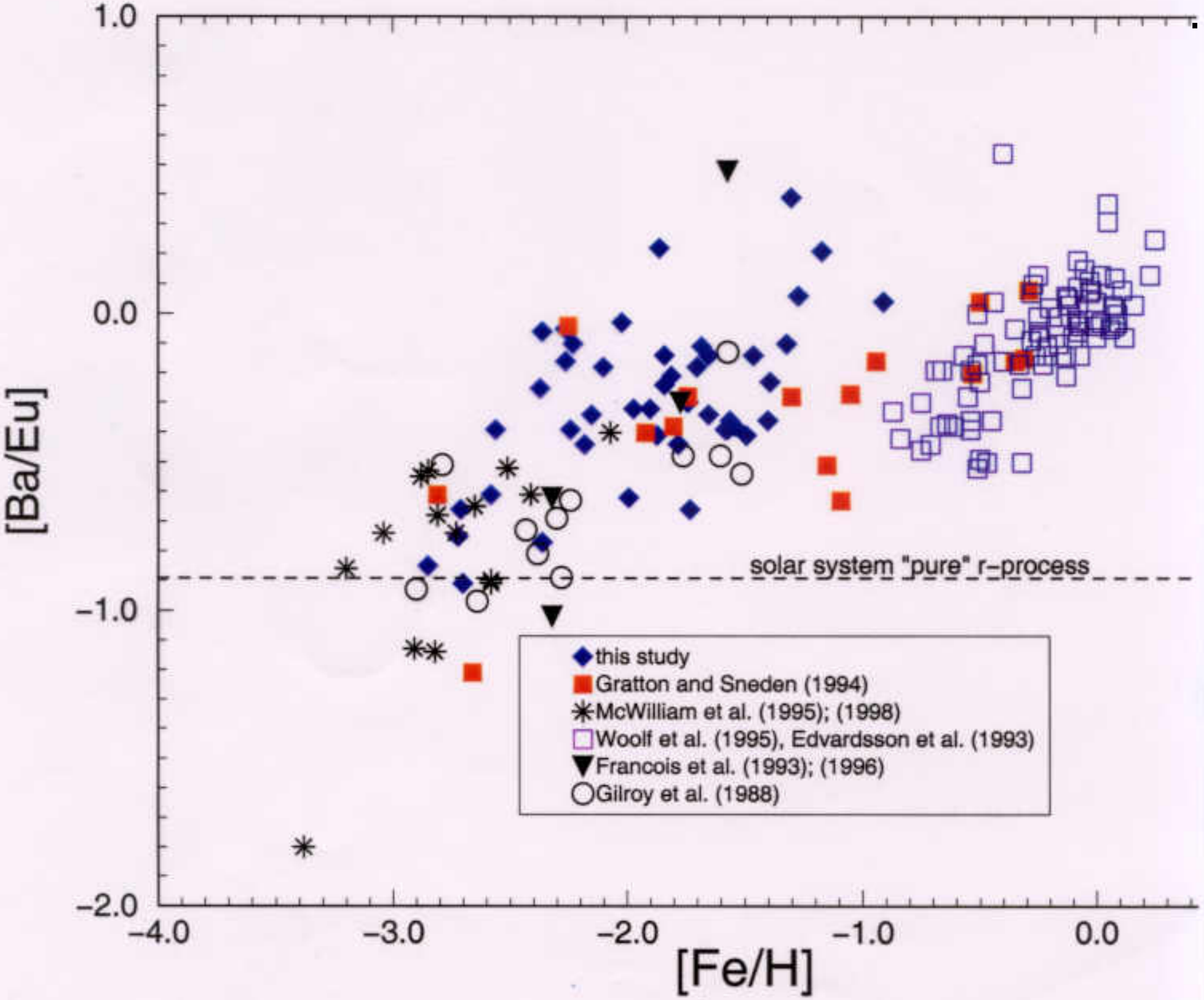
Mg, like O, is uniquely a product of massive star nucleosynthesis. Fe comes from massive stars plus Type Ia supernovae (Barbuy et al (2018)

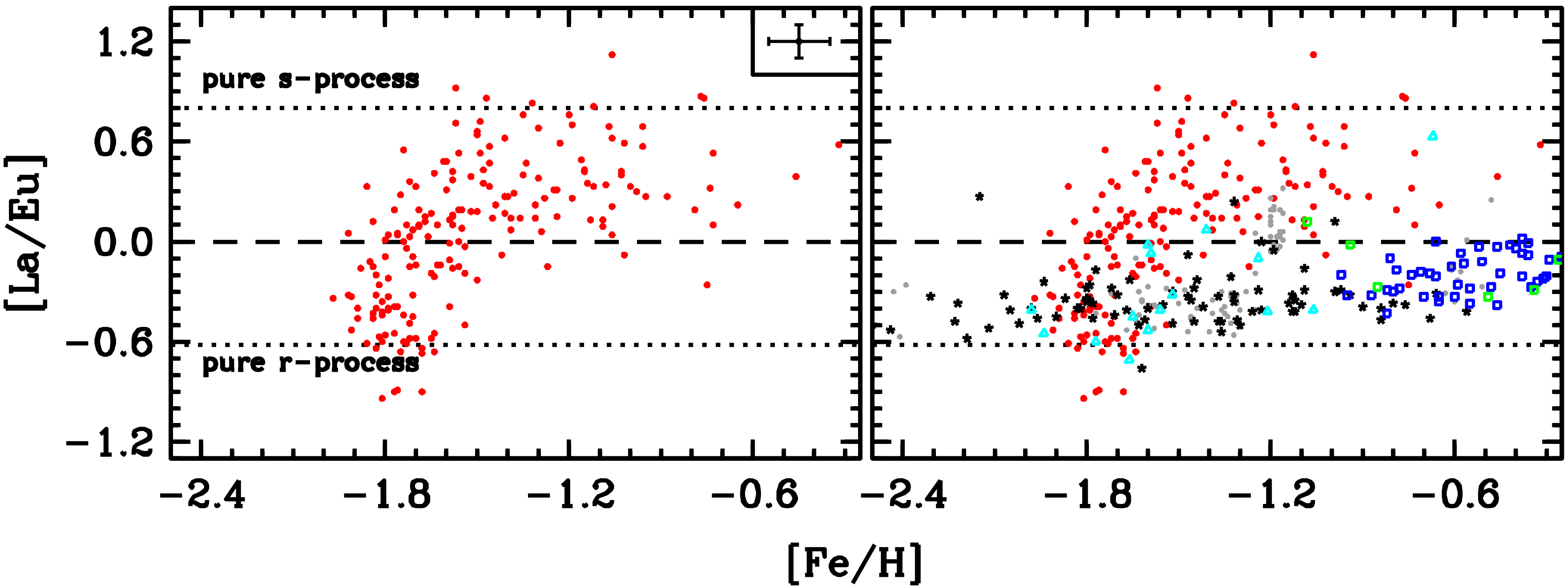


Mn is a bit of a puzzle but may come mostly now from SN Ia and is underproduced relative to Fe in massive stars.



Frebel et al (2010) for stars in two very faint dwarf galaxies Ursa Major 2 and Coma Berenices. Ba is a product of the s-process.


1.0
0.0
−1.0
−2.0
[Ba/Eu]
−4.0
−3.0
−2.0
−1.0
0.0
[Fe/H]
solar system "pure" r–process
◆ this study
■ Gratton and Sneden (1994)
✳ McWilliam et al. (1995); (1998)
□ Woolf et al. (1995), Edvardsson et al. (1993)
▼ Francois et al. (1993); (1996)
○ Gilroy et al. (1988)



Johnson and Pilochowski (2010). ω-Cen is red points. Galactic and other measurements on the right. La is predominantly s-process and Eu is mainly r-process.

The inference is that as one goes back in time the r-process (TBD) arose earlier than the s-process (TBD)

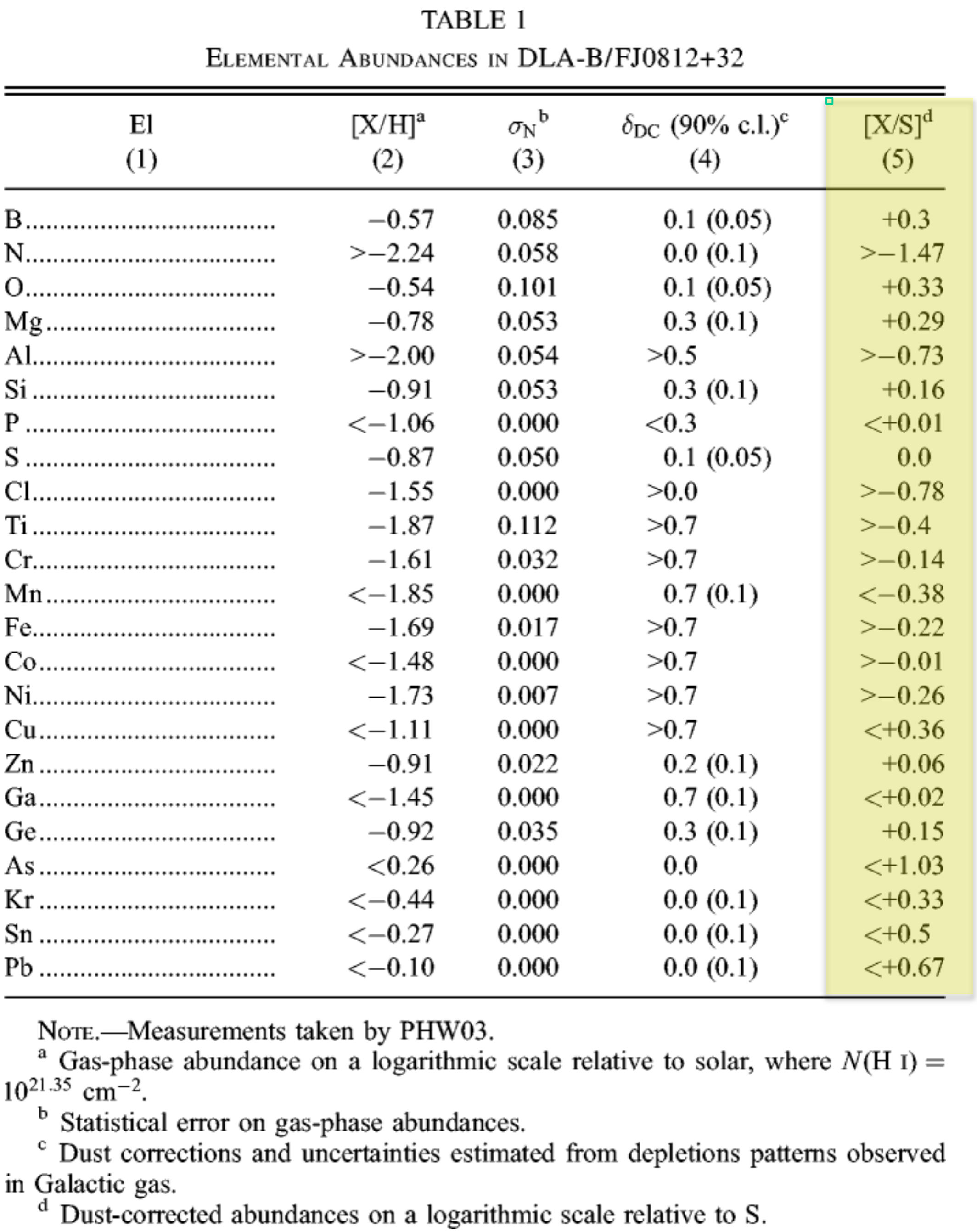


TABLE 1

ELEMENTAL ABUNDANCES IN DLA-B/FJ0812+32

El (1)	[X/H][a] (2)	σ_N[b] (3)	δ_{DC} (90% c.l.)[c] (4)	[X/S][d] (5)
B	−0.57	0.085	0.1 (0.05)	+0.3
N	>−2.24	0.058	0.0 (0.1)	>−1.47
O	−0.54	0.101	0.1 (0.05)	+0.33
Mg	−0.78	0.053	0.3 (0.1)	+0.29
Al	>−2.00	0.054	>0.5	>−0.73
Si	−0.91	0.053	0.3 (0.1)	+0.16
P	<−1.06	0.000	<0.3	<+0.01
S	−0.87	0.050	0.1 (0.05)	0.0
Cl	−1.55	0.000	>0.0	>−0.78
Ti	−1.87	0.112	>0.7	>−0.4
Cr	−1.61	0.032	>0.7	>−0.14
Mn	<−1.85	0.000	0.7 (0.1)	<−0.38
Fe	−1.69	0.017	>0.7	>−0.22
Co	<−1.48	0.000	>0.7	>−0.01
Ni	−1.73	0.007	>0.7	>−0.26
Cu	<−1.11	0.000	>0.7	<+0.36
Zn	−0.91	0.022	0.2 (0.1)	+0.06
Ga	<−1.45	0.000	0.7 (0.1)	<+0.02
Ge	−0.92	0.035	0.3 (0.1)	+0.15
As	<0.26	0.000	0.0	<+1.03
Kr	<−0.44	0.000	0.0 (0.1)	<+0.33
Sn	<−0.27	0.000	0.0 (0.1)	<+0.5
Pb	<−0.10	0.000	0.0 (0.1)	<+0.67

NOTE.—Measurements taken by PHW03.

[a] Gas-phase abundance on a logarithmic scale relative to solar, where $N(\text{H I}) = 10^{21.35}$ cm^{-2}.

[b] Statistical error on gas-phase abundances.

[c] Dust corrections and uncertainties estimated from depletions patterns observed in Galactic gas.

[d] Dust-corrected abundances on a logarithmic scale relative to S.

Abundances in a damped Ly-alpha system at redshift 2.626. 20 elements.

Metallicity ~ 1/3 solar

Fenner, Prochaska, and Gibson, ApJ, 606, 116, (2004)

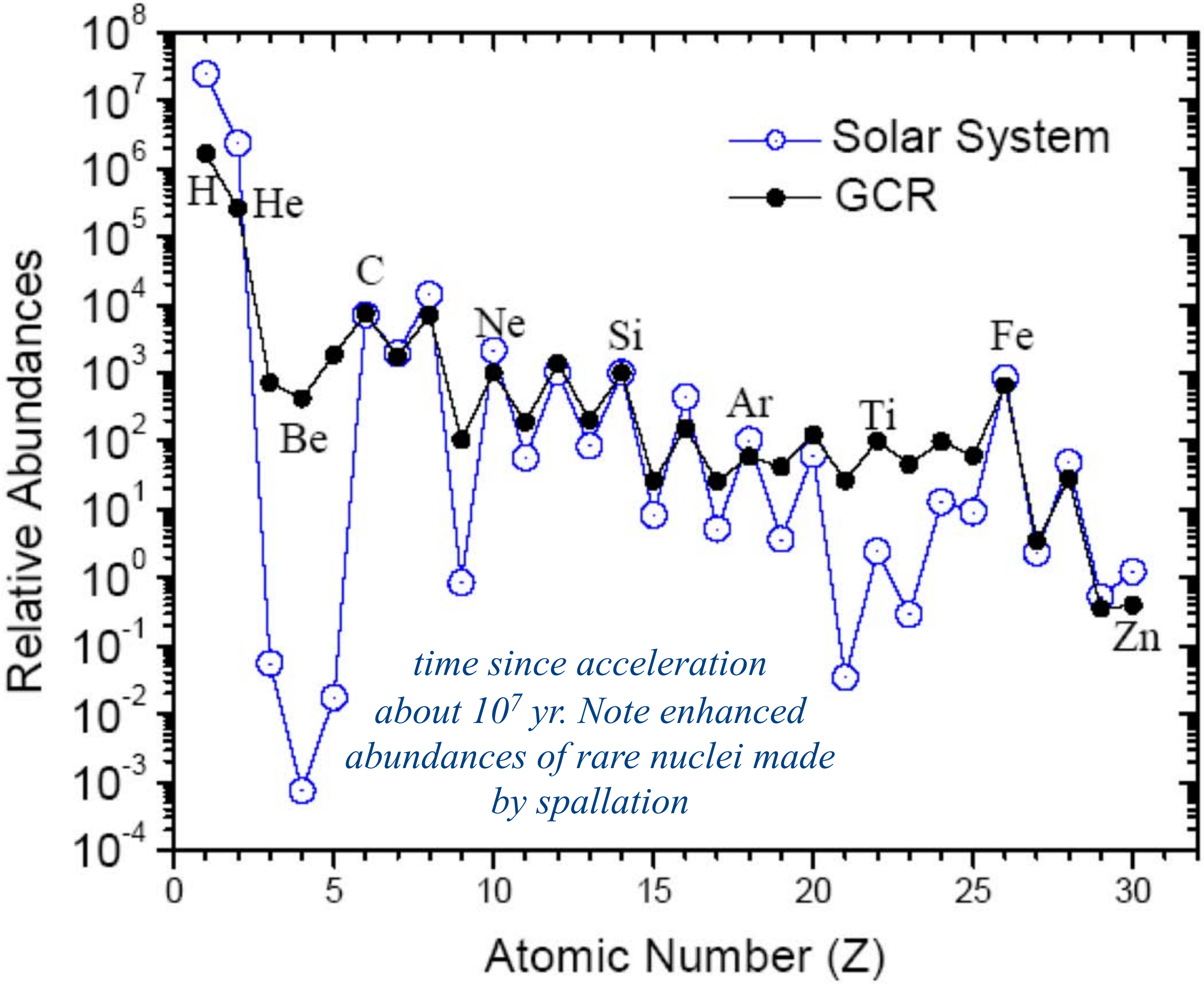
Even the abundances as far away as we can see have an abundance pattern similar to the sun.

Nucleosynthesis is a robust process.

Abundances of cosmic rays arriving at Earth

http://www.srl.caltech.edu/ACE/

Advanced Composition Explorer (1997 - 1998)



time since acceleration about 10^7 *yr. Note enhanced abundances of rare nuclei made by spallation*