Solar System Abundances of the Elements

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NIC 2018

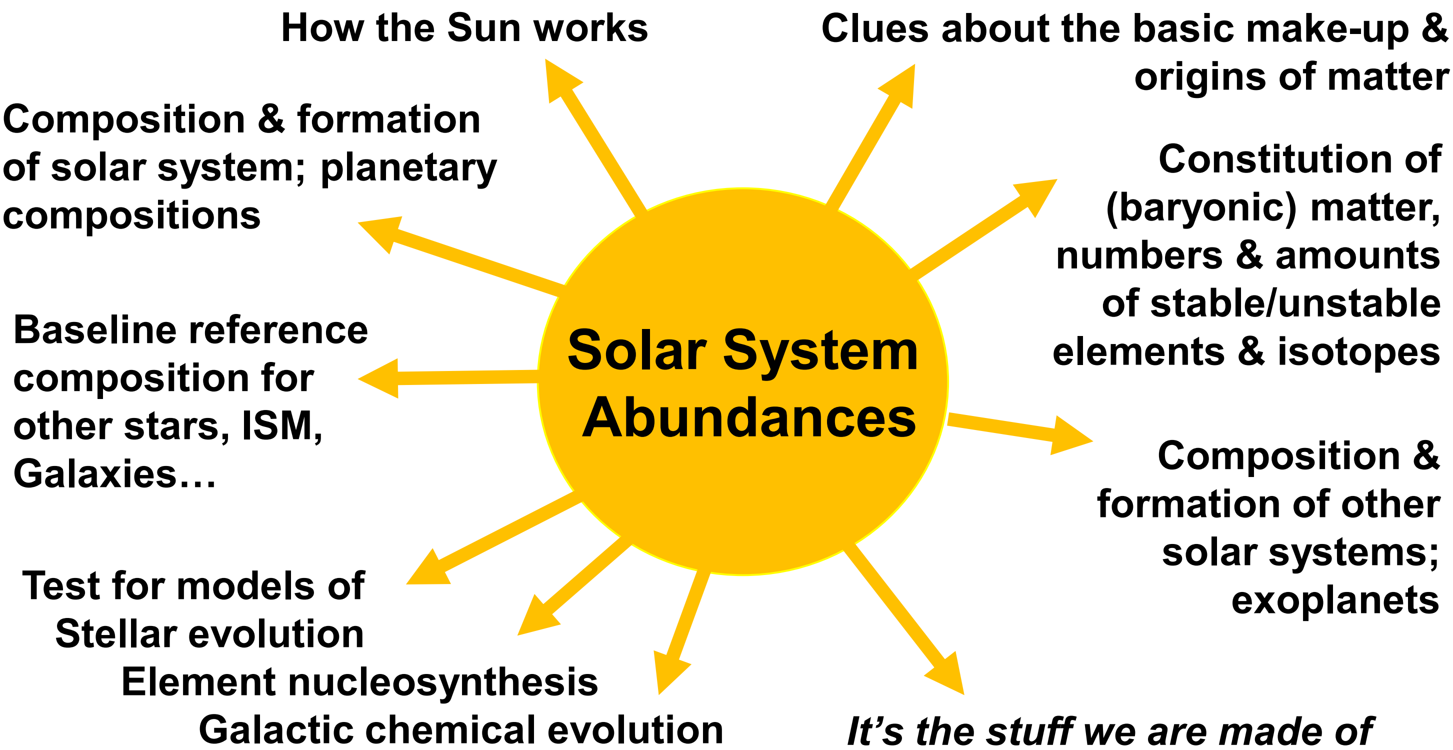
Overview

The Elements

Abundances

Challenges: Solar & Meteoritic

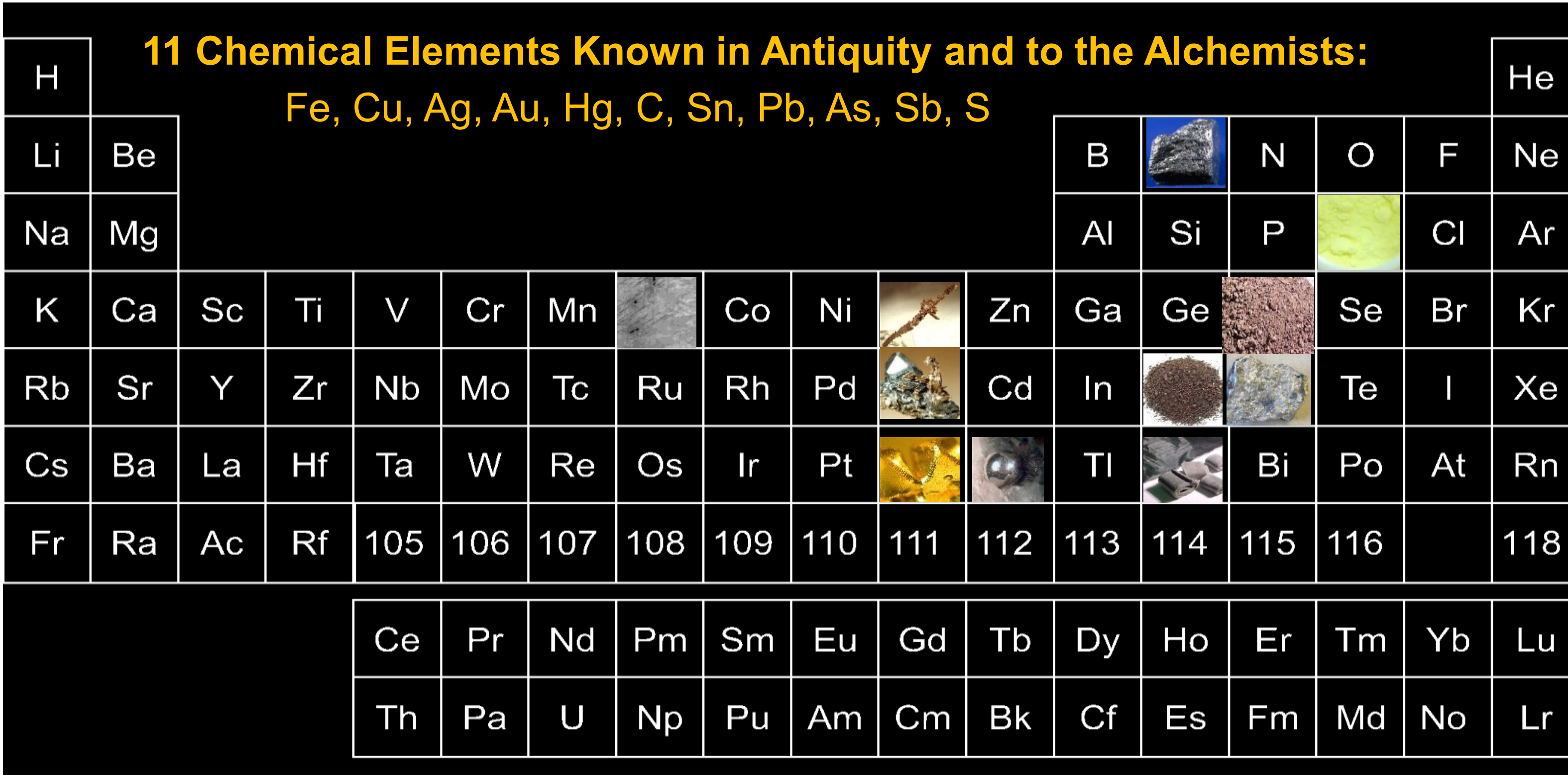
Why Solar System Abundances of the Elements?



How Many Elements?

Aristotle's periodic table of the elements

Air	Fire
Earth	Water



Today: 83 Stable and Long-lived Chemical Elements

Yes, 117 is there now too…

1847 ~59 elements known

16 abundant elements common to different crustal rocks, ore deposits, mineral & ocean waters, meteorites, & organic matter:

H, Na, K, Mg, Ca, Al, C, Si, N, P, O, S, F, Cl, Mn, Fe

"This identity shows that the surface of the Earth encloses in all its parts everything that is essential for the existence of organized beings...

... one sees that nature has provided not only a settlement but also the conservation of this indispensable harmony.

The aging Earth will never cease to furnish all the elements to the organized beings necessary for their existence"

Elie de Beaumont, 1847

later:

spectral analysis 1860s

Mendeleev's periodic table 1869

1885 68 elements known

Periodic table is established

I. A. Kleiber: Do the same elements occur in other celestial objects?

Compare:
Earth’s crust
Meteorites
Comets
Meteors
Sun
Other stars

Composition of celestial objects is not random… So is there a universal composition? Where from?

Sign Convention:

●	Elements detected in celestial bodies	-	Elements not detected in celestial bodies	?	Presence of elements is very uncertain	○	Presence of elements is uncertain

I.A. Kleiber's table on the chemical composition of celestial bodies 1885

H ●										
Zi ●	Be ●	B	C ●	N ●	O ●	F ●				
Na ●	Mg ●	Al ●	Si ●	P ●	S ●	Cl ●				
K ●	Ca ●	Sc ?	Ti ●	V ●	Cn ●	Mn ●	Fe ●	Co ●	Ni ●	Cu ●
(Cu) ●	Zn ●	Ga ?		As ●	Se ●	Br ●				
Rb	Sr ●	Yt ●	Zr ●	Nb ?	Mo ●		Ru ?	Rh ?	Pt ●	Ag ○
(Ag) ○	Cd ●	In ●	Sn ●	Sb ●	Te ●	I -				
Cs ●	Ba ●	La ●	Ce ●	Di -						
		Er -		Ta ?	W -		Os -	Ir -	Pt -	Au -
(Au) -	Hg ●	Tl -	Pb ●	Bi ●						
			Th -		U ●					

Helium found in 1868 but not plotted, no other noble gases known at the time

83 elements…
… 83 problems

all stable elements up to atomic number 83 (Bi)
plus long-lived radioactive Th and U.

Where do Abundance Numbers Come From?

F. W. Clarke 1889, Clarke and H. S. Washington, 1922 Composition of the Earth's Crust *Proc. National Acad. Sci.*, **8,** 114

Use Composition of Earth's crust?

Plenty available material for lab analyses but
- crust not representative of entire differentiated(!) and geologically active Earth
- Earth is not representative for total solar system composition (volatiles!)

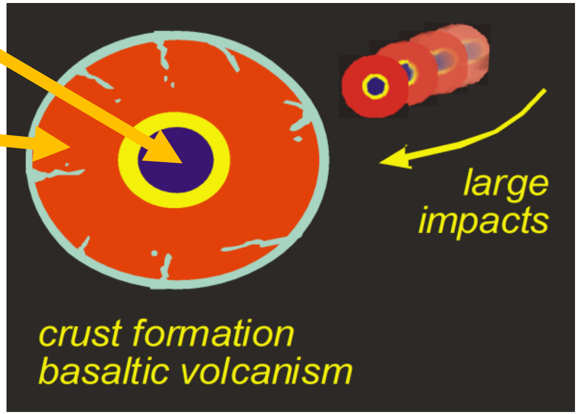
Loss of Volatile Elements (C,N,O, noble gases, halogens, alkalis et al.)
Elements are distributed between core, silicate mantle and crust

Geochemical affinities; Goldschmidt 1920s,1930s

Metallic elements Fe, Ni, Co, Au, Ir,… to core

Silicate rock-forming elements to silicate mantle and crust
Mg, Si, (Fe), Al, Ca, Ti, REE…

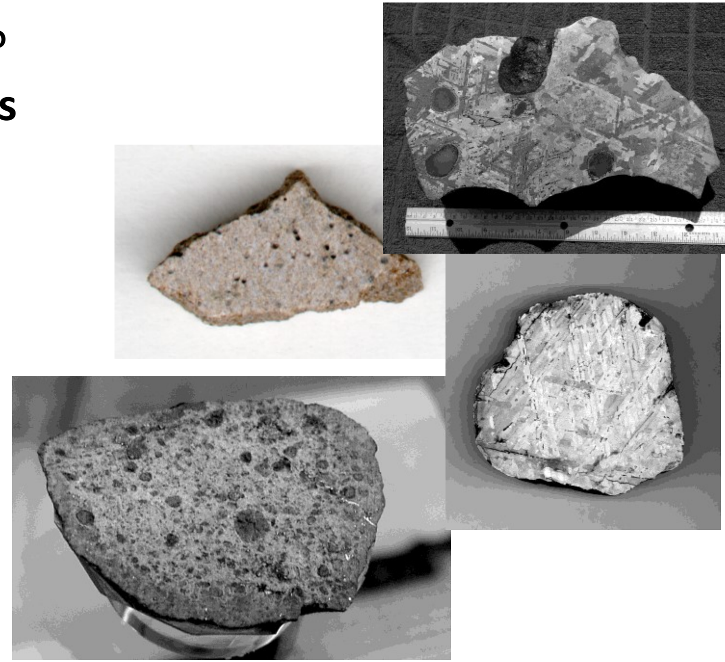
Incompatible (large ionic radii, charge) elements enter silicate melts, into crust
Si, Al, Ca, K, Na, REE, U, Th …



Meteorites as “universal or cosmic” elemental standards

1796 Chladni suspects meteorites as “Weltenspäne”

Representative Meteoritic Composition = ?
mix of silicate, metal, sulfide compositions



Farrington; Merrill (1915)
Harkins (1917) stones & irons
Goldschmidt (1922, 34,37) 10:2:1
I. & W. Noddack (1930s) 82.5:12:5.5
Prior (1933) 85:9:6
H. Brown (1949)

Urey (1951/52)
use "conventional" 85:9.5:5.5 or,
better, direct chondrite values as Noddacks did in 1934/35

(analysis methods)

1917 Harkins: Meteorites as "universal or cosmic" elemental standards

average of <u>stony meteorites</u> (not irons)

no photospheric abundances yet!

Plot abundances vs. atomic number:

Li, B, Be (3-5) are below scale
C (6) low because of **volatility**, but still more abundant than odd numbered neighbors B (5) or N (7)

Abundances **peak again at Fe (26)**

Abundances of elements heavier than Fe (26) are quite low

Even-numbered elements are more abundant than their odd-numbered neighbors

Nuclear vs. electronic

Harkins' discovery graph

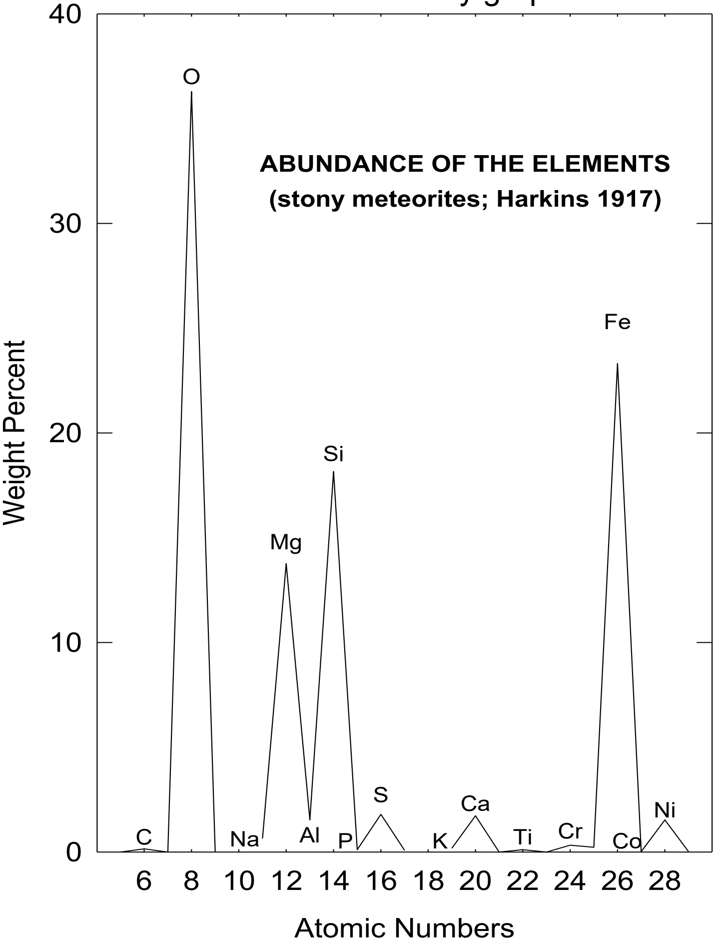


Fig. 1.—The abundance of the elements in the stone meteorites. Every even-numbered element is more abundant than the two adjacent odd-numbered elements.

1929 H.N. Russell First Detailed Solar Photospheric Abundances

"Abundances in Sun resemble that in meteorites more closely than in the Earth's outer layers"

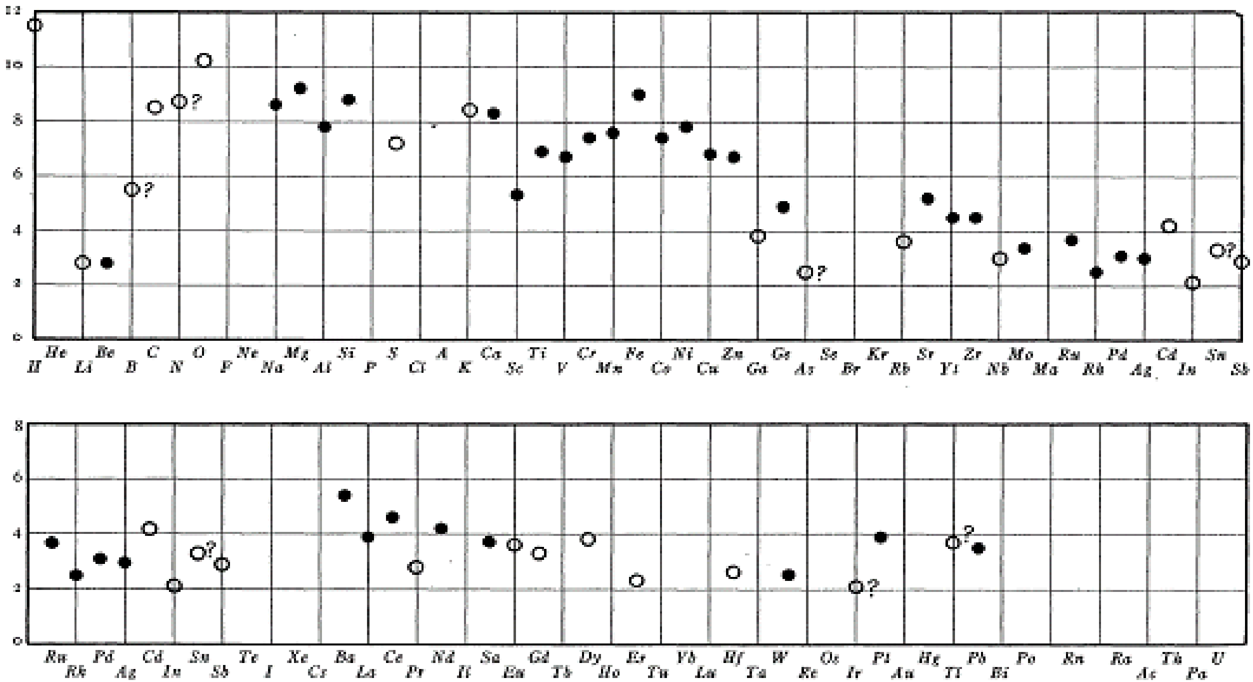


FIG. 3.—Values of log Q, where Q represents the total mass of the atoms or molecules of an element per unit area of the sun's surface.

Sun has > 99% of the solar system's mass, should be good average composition for solar system as a whole

Abundances by *mass/surface area; 65*

1949 H. Brown

Meteoritic and Solar

"Meteoritic" from weighted average of elements in silicate:metal+sulfide = 1/3 : 2/3

Proportions chosen to match densities of terrestrial planets (not the best choice)

Iron in Sun problem…
(resolved in late 1960s)

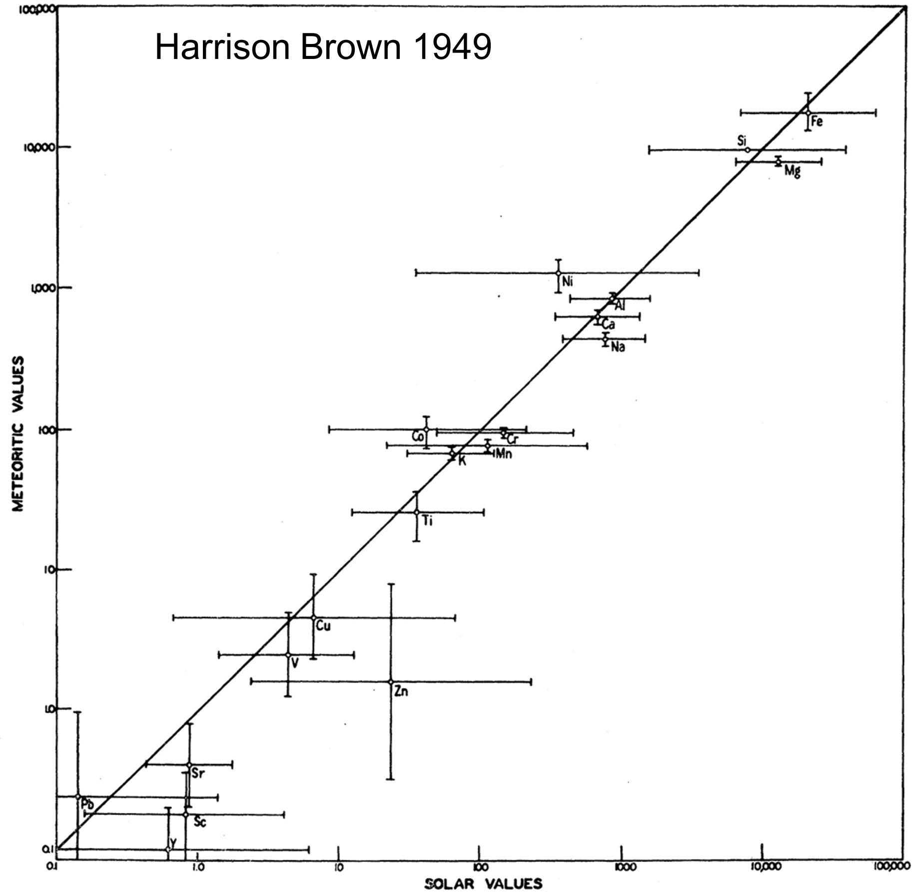


FIG. 2. The concentrations of various elements in meteorites compared with concentrations in the solar atmosphere. The values have been normalized by setting solar calcium equal to meteoritic calcium. The lengths of the lines designate the estimates of the limits of error.

Both scales normalized to 670 Calcium atoms

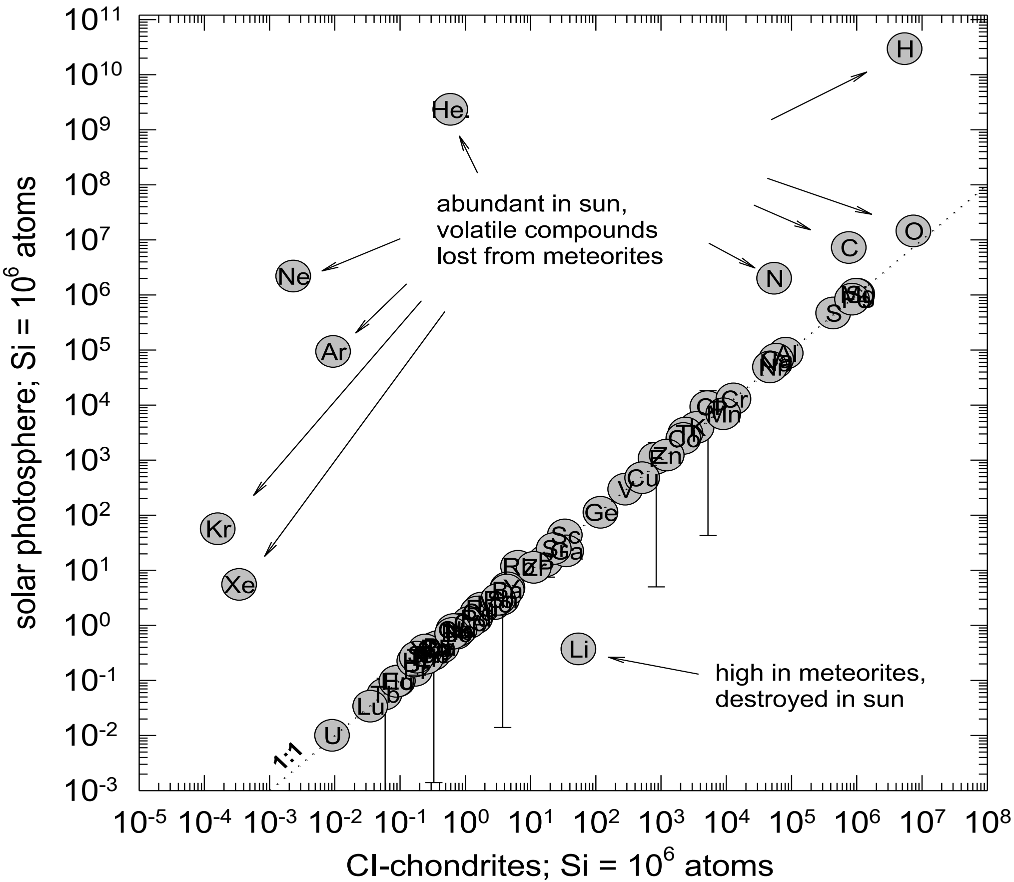
Meteoritic and Solar

Good correlation for heavy elements along 1:1 line – on log-log plot…

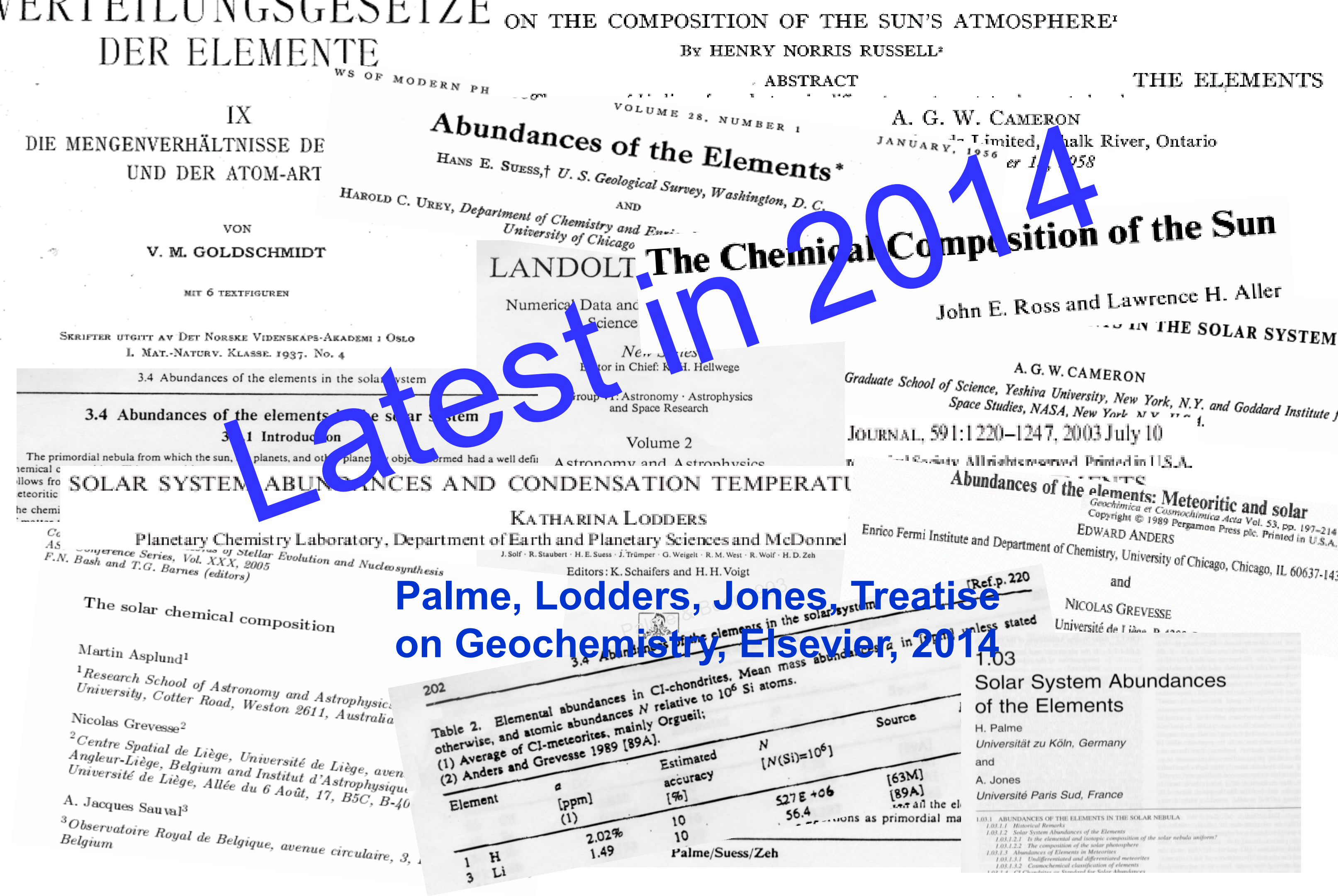
Meteorites depleted in elements forming volatile compounds
  CO, CH_4, N_2, H_2O, also noble gases

Sun depleted in Li

➔Use abundances in CI-chondrites to get representative elemental data



Both scales normalized to 1e6 Si atoms, Figure from Lodders & Fegley 2011, Chemistry of the Solar System, RSC


Latest in 2014
Palme, Lodders, Jones, Treatise on Geochemistry, Elsevier, 2014
VERTEILUNGSGESETZE DER ELEMENTE
IX
DIE MENGENVERHÄLTNISSE DE
UND DER ATOM-ART
VON
V. M. GOLDSCHMIDT
MIT 6 TEXTFIGUREN
SKRIFTER UTGITT AV DET NORSKE VIDENSKAPS-AKADEMI I OSLO
I. MAT.-NATURV. KLASSE. 1937. No. 4
ON THE COMPOSITION OF THE SUN'S ATMOSPHERE
BY HENRY NORRIS RUSSELL
ABSTRACT
THE ELEMENTS
A. G. W. CAMERON
VOLUME 28, NUMBER 1
JANUARY, 1956
Abundances of the Elements*
HANS E. SUESS,† U. S. Geological Survey, Washington, D. C.
AND
HAROLD C. UREY, Department of Chemistry and
University of Chicago
LANDOLT
Numerical Data and
Science
New Series
Editor in Chief: K.-H. Hellwege
Group VI: Astronomy · Astrophysics and Space Research
Volume 2
Astronomy and Astrophysics
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Editors: K. Schaifers and H. H. Voigt
The Chemical Composition of the Sun
John E. Ross and Lawrence H. Aller
THE SOLAR SYSTEM
A. G. W. CAMERON
Graduate School of Science, Yeshiva University, New York, N.Y. and Goddard Institute
Space Studies, NASA, New York
JOURNAL, 591:1220–1247, 2003 July 10
3.4 Abundances of the elements in the solar system
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SOLAR SYSTEM ABUNDANCES AND CONDENSATION TEMPERATU
KATHARINA LODDERS
Planetary Chemistry Laboratory, Department of Earth and Planetary Sciences and McDonnel
Abundances of the elements: Meteoritic and solar
Geochimica et Cosmochimica Acta Vol. 53, pp. 197–214
Copyright © 1989 Pergamon Press plc. Printed in U.S.A.
EDWARD ANDERS
Enrico Fermi Institute and Department of Chemistry, University of Chicago, Chicago, IL 60637-143
and
NICOLAS GREVESSE
Conference Series, Vol. XXX, 2005
F.N. Bash and T.G. Barnes (editors)
The solar chemical composition
Martin Asplund[1]
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University, Cotter Road, Weston 2611, Australia
Nicolas Grevesse[2]
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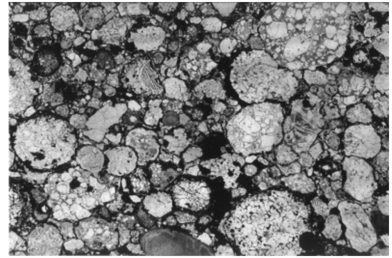
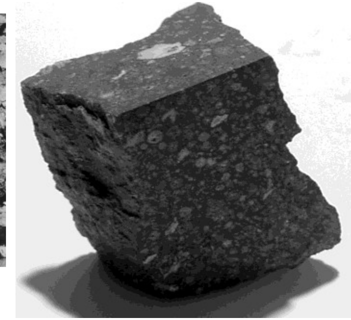
Belgium
202
Table 2. Elemental abundances in CI-chondrites, Mean mass abundances
otherwise, and atomic abundances N relative to 10^6 Si atoms.
(1) Average of CI-meteorites, mainly Orgueil;
(2) Anders and Grevesse 1989 [89A].
Palme/Suess/Zeh
1.03
Solar System Abundances of the Elements
H. Palme
Universität zu Köln, Germany
and
A. Jones
Université Paris Sud, France

Representative Meteoritic Composition

Use chondrite averages
Harkins 1917
I & W. Noddack 1935
Brown & Patterson 1947
Urey & Craig 1956



Chondrules in Tieschitz ordinary chondrite. Field of view ca. 5-6 mm



Allende CV chondrite ca. 3 cm wide

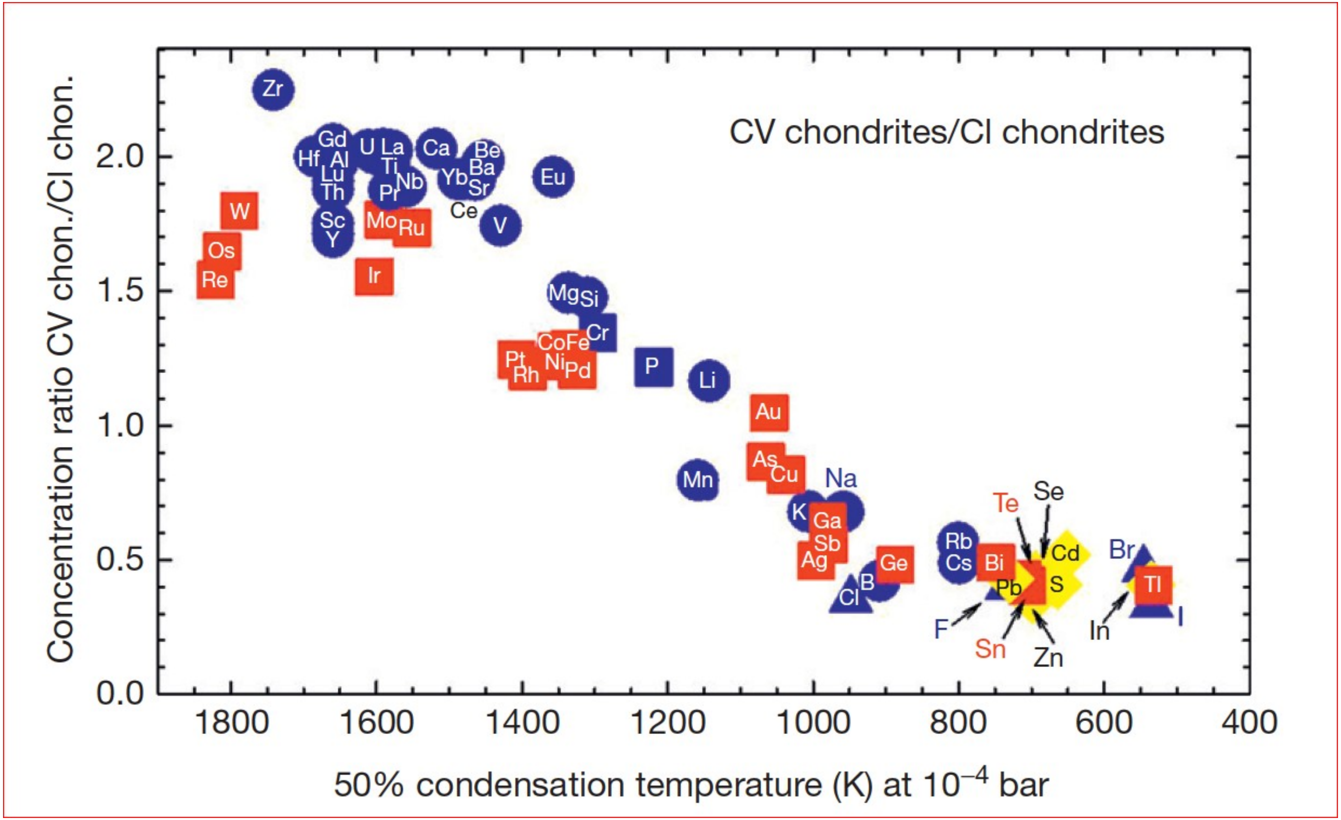
Use CI-chondrites: Urey 1950s
CI chondrite standard established by early 1970s

Only 5 observed CI1 chondrite falls:
Alais 1806 (6 kg) Ivuna 1938 (0.7 kg)
Orgueil 1864 (14 kg)
Revelstoke 1965 (1 g) Tonk 1911 (10 g)

Ivuna CI1 chondrite

CI-chondrites looked at by Berzelius 1835 (Alais), Daubree 1864 (Orgueil), others, suspect that these rocks may be close to "primeval matter"

CI Chondrites are the most volatile-rich meteorites; other chondrite groups show volatility related element fractionations relative to CI chondrites:



Independent of geochemical character

CI chondrites are primitive with regard to chemical composition but not mineralogically; yet aqueous mineral alterations did not change overall *elemental* composition on CI-chondrites parent bodies

CLOSED SYSTEM

"… a carbonaceous chondrite… a material as perishable as the alchemist's earth, air, fire, and water and not very stable in any of these media".

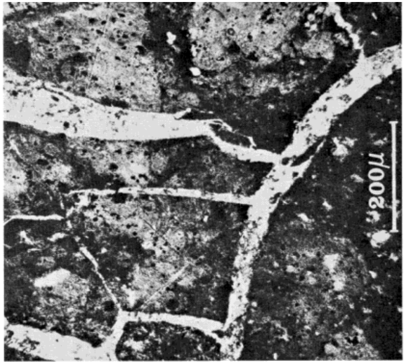
Folinsbee, 1967

Case Study: Sulfur

occurs in Sulfides, Sulfates, Organics

Ongoing (!) terrestrial oxidation of metal & sulfide changes amount of S-bearing phases

e.g., - sulfides, + sulfates, +free S



Richardson 1978

Will this affect *bulk* S determinations?

No - while amounts of S-bearing phases change, whole rock-S-contents seem to be preserved in *larger*, *sub-surface* samples

Yes – if analysis method is selective only to a particular phase

Any losses/gains during storage?

Terrestrial oxidation of sulfide & metal, and sulfate hydration

=> *total mass* of rock changes,

but *relative amounts* of elements other than O and H do not

Sulfur in the CI chondrite Orgueil:

16 concentration measurements done between 1864 and 2000 range from about 2 to 7 mass% - indicates analytical problems.

<u>Partial analyses and/or sampling bias:</u>

Selective phase dissolution/combustion:

only quantitative for certain S-bearing phases,
but not always quantitative for whole-rock S abundance: → low totals

Use of smaller and/or selected matrix samples from which S may have been lost as sulfate to veins or exterior: → low totals

Sample heterogeneities/multiple analysis methods on one sample: → mixed results

DuFresne & Anders 1962; Kaplan & Hulston 1966; Burgess et al. 1991, Gao & Thiemens 1993

<u>Whole rock S analyses:</u>

Good for total S abundances, but no or limited info on S distribution among phases

Whole rock S abundances often done on aliquots from larger (g-size) homogenized samples

3 analyses in 1864; data by Wiik 1956,1962; Jarosewich 1972; Dreibus et al. 1993,1995

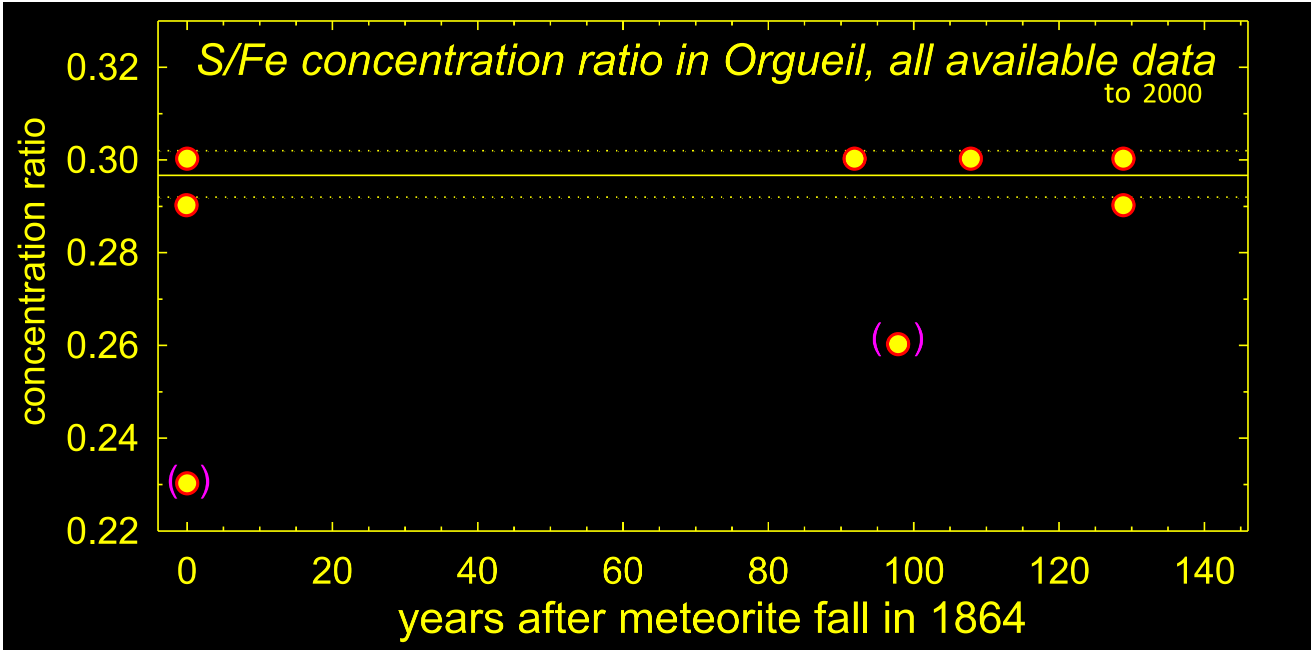
use S/element ratio to avoid uncertainties in absolute concentration from samples with different water content.

S/Fe ratios in Orgueil from 8 analyses: No obvious decrease of *bulk* S/Fe with time

No obvious S loss from samples analyzed

Average of 6 analyses: S/Fe ~0.30±0.01 → **S = 5.67 wt%**

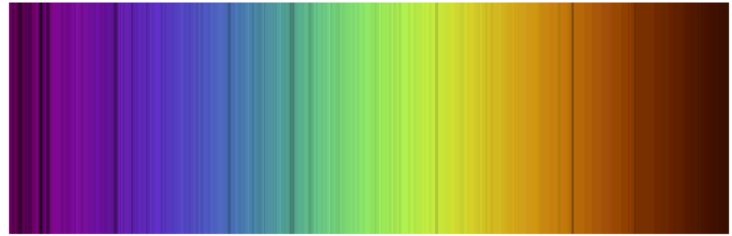
(for adopted Fe=18.9%)



have 2 more values from 2012, give same average. Excluded () are 0.26 Wiik 1962 AMNH, 5.02 S; and |
0.23 Cloez 1864. weeks after fall, dried sample, S 5.58, higher Fe in both

Where do the solar system abundance numbers come from?

Photos **web**, Musee d'Histoire(?)



Meteorites: CI Chondrites
(non-volatile elements only)

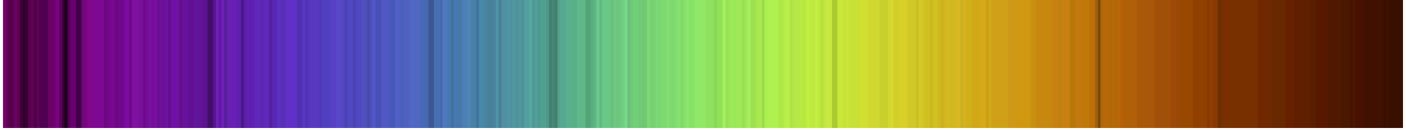
Sun: Solar photospheric spectrum
Sunspots, Solar Wind

Other solar system objects: gas-giant planets, comets, IDPs, meteors
Presolar grains (genuine star dust) found in meteorites

Spectra of other dwarf stars (B - M stars)
Planetary Nebulae (PN)
Galactic Cosmic Rays

Interstellar medium
Supernova Remnants

Theory!!



~68 out of 83 naturally occurring elements in the Sun's Photosphere

Present as neutral atoms and ions. Few molecules

~30 – 35 elements ±well determined in photosphere

Uncertainties:

> 0.10 dex: (factor 1.3)

Li, Be, B, N, Sc, Cr, Ni, Zn, Ga, Rh, Cd, In, Nd, Tb, Ho, Tm, Yb, Lu, Os, Pt

> 0.05 dex: (factor 1.12)

Mg, Al, Si, Ti, Fe, Co, Nb, Ru, Ba, Ce, Pr, Dy, Er, Hf, Pb

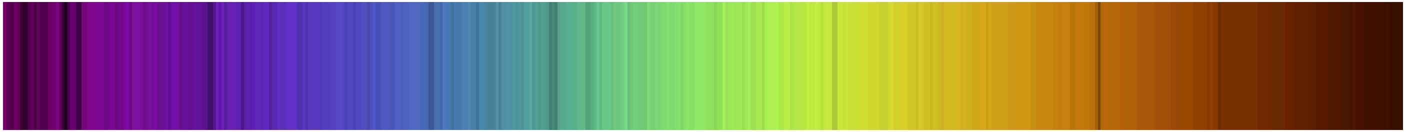
Difficult to determine (line blends, low abundance, no lines)

Ag, In, Sn, Sb, W, Au, Th, U; As, Se, Br, Te, I, Cs, Ta, Re, Hg, Bi

He detected but difficult to quantify from spectra; need helioseismology

He, Ne, Ar, Kr, Xe found in solar wind

Determined in Sun-spot spectra, relatively uncertain: F, Cl, In, Tl



Challenges for photospheric abundance determinations

Line list for energy levels of neutral atoms, ions, electronic & excited state transitions

    Fe several thousand lines, other elements only 1 line accessible

Line blending

    Ni and Fe lines interfere; e.g., determinations of O, Th

Transition probabilities and lifetimes of atomic states

    re-analysis of transition metals and REE

LTE vs. non LTE - Is radiation in local equilibrium with matter?

    Saha: $E + M \rightarrow E^{+} + e^{-} + M$ (ionization)

    Boltzmann: $E+M \rightarrow E^{*} + M$ (excitation)

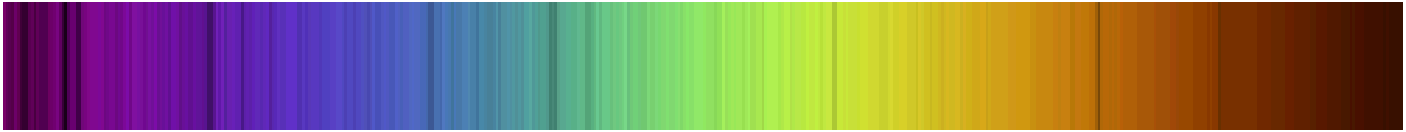
Settling effects over solar lifetime

Atmospheric models (T,P, r)

    1D, 3D; variability, granulation, convection zone (Li)

    continuum modeling (e.g., UV for Be)

    3D Hydrodynamic, vs 3D Hydro-magneto-dynamic



Photospheric Abundance Determinations in the past two decades:

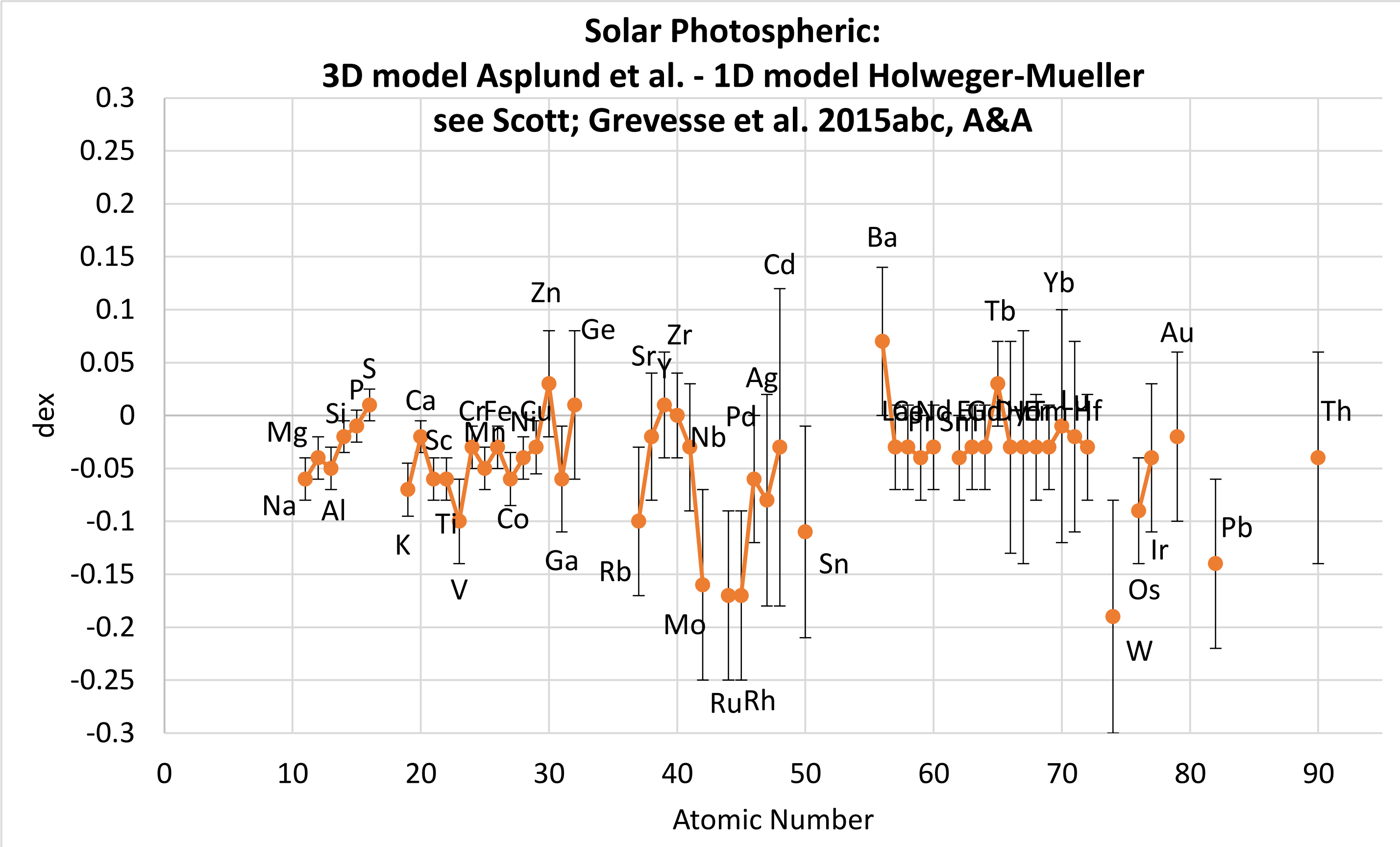
Better models for NLTE effects
Evolved 3D atmospheric models: Asplund, Ayres, Caffau,Ludwig, Steffen…
3D-time dependent hydro-dynamical atmosphere models, e.g., Pereira et al. 2009
Magnetic field effects; temperature stratifications, e.g., Fabbian et al. 2015

Major Changes:

Lower C,N,O, Ne; “Oxygen crisis” Allende-Pietro, Asplund, Ayres

Heavy element mass fraction Z from 0.02 to 0.13 (0.
Standard Solar Model from Helioseismology now has problems, missing opacity
(see Serinelli 2010 for solar models)

3D models more realistic, but abundance determinations still not fully accepted

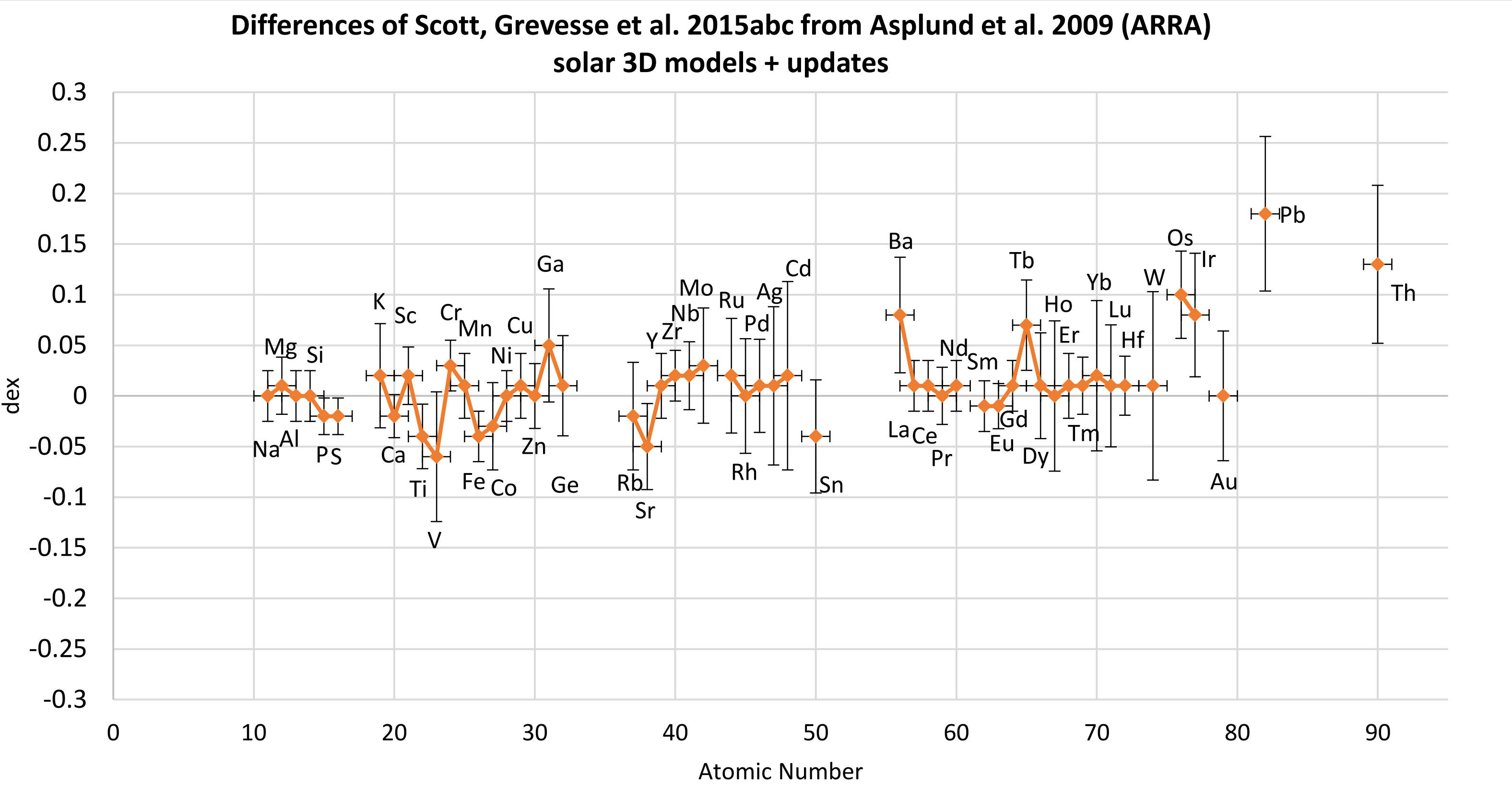


3D corrections reduce abundances within 0.05 dex for most; Mo, Ru, Rh, W, Pb reduced within 0.2 dex.

Increase within 0.05 dex for Zn, B, Tb, Ge, Y; Ba somewhat larger.

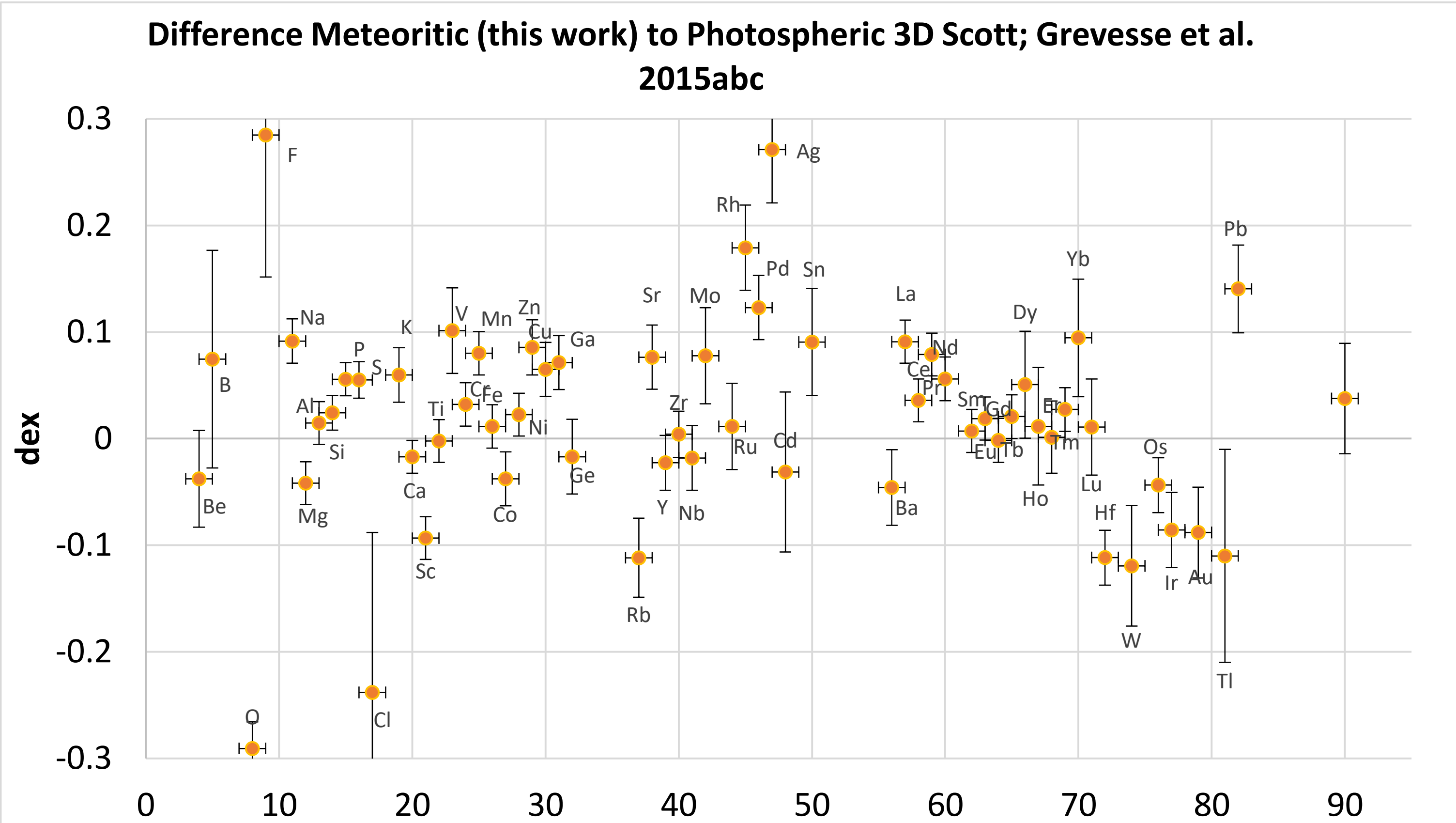
Uncertainties shown are for 3D only - often comparable to spread.

Grevesse, N., Scott, P., Asplund, M. Sauval, A. J. 2015, A&A 573, id A27 part III



Differences mainly due to NLTE corrections, line selections. Variations are within 0.05 dex (factor 1.12) for most.

Asplund et al. 2009 (ARRA) updates in Scott, P.; Grevesse, N., Asplund, M., Sauval, A.J., Lind, K., Takeda, Y., Collet, R., Trampedach, R., Hayek, W. 2015, A&A, 573, idA25. Scott, P., Asplund, M., Grevesse, N., Bergemann, M., Sauval, A.J. 2015, 573, id.A26. Grevesse, N., Scott, P., Asplund, M. Sauval, A. J. 2015, A&A 573, id A27.



Difference Meteoritic (this work) to Photospheric 3D Scott; Grevesse et al. 2015abc
dex
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
0
10
20
30
40
50
60
70
80
90
F
Ag
Rh
Pb
Pd
Sn
Yb
B
Na
K
V
Mn
Zn
Cu
Ga
Sr
Mo
La
Dy
Nd
Ce
Pr
P
S
Al
Si
Ti
Cr
Fe
Ni
Zr
Ru
Cd
Sm
Gd
Er
Eu
Tb
Tm
Ho
Lu
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Sc
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O
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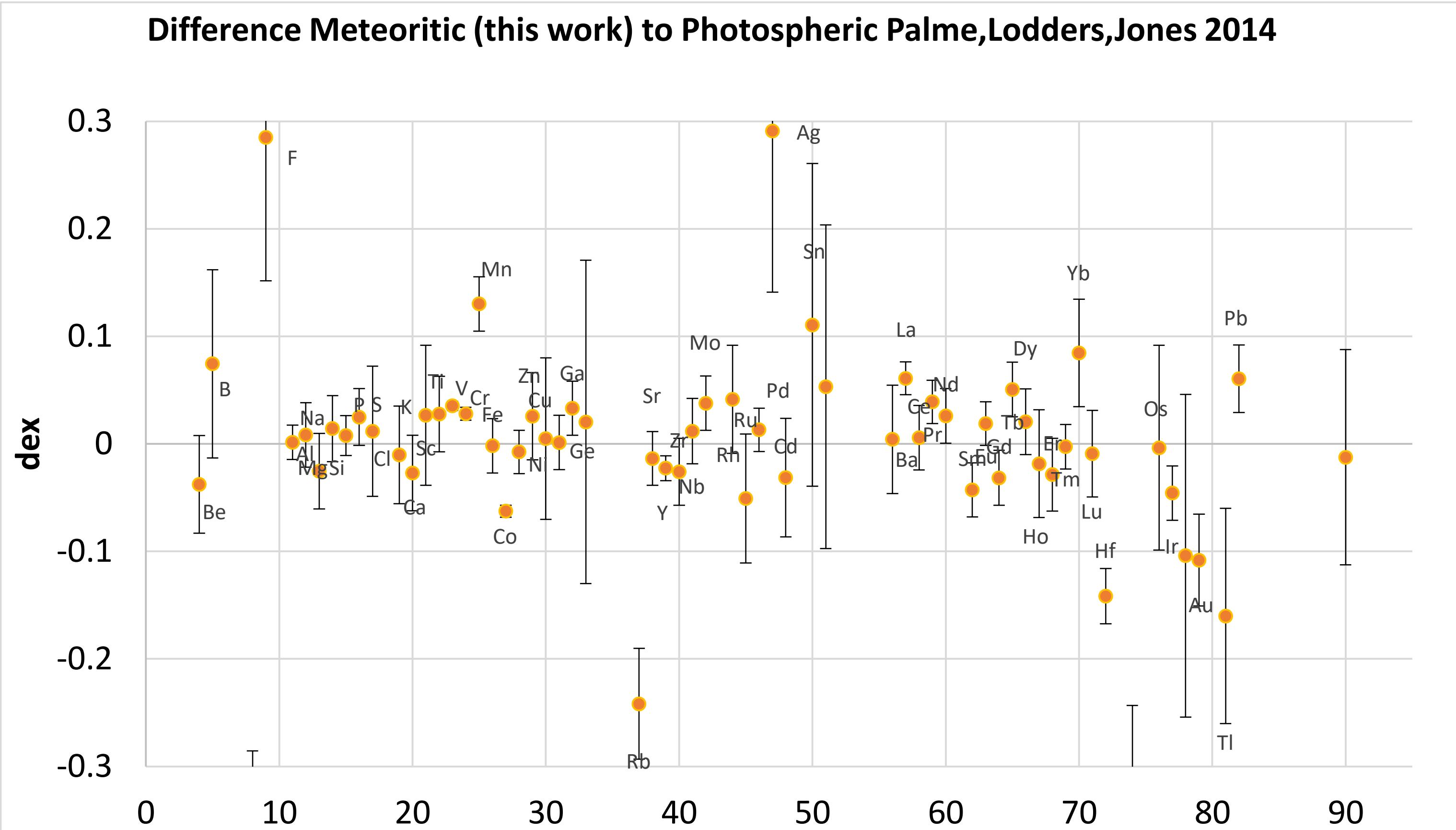
Difference Meteoritic (this work) to Photospheric Palme,Lodders,Jones 2014
dex
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
0
10
20
30
40
50
60
70
80
90
Be
B
F
Na
Al
Mg
Si
P
S
Cl
K
Ca
Sc
Ti
V
Cr
Mn
Fe
Co
Ni
Cu
Zn
Ga
Ge
Rb
Sr
Y
Zr
Nb
Mo
Ru
Rh
Pd
Ag
Cd
Sn
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Os
Ir
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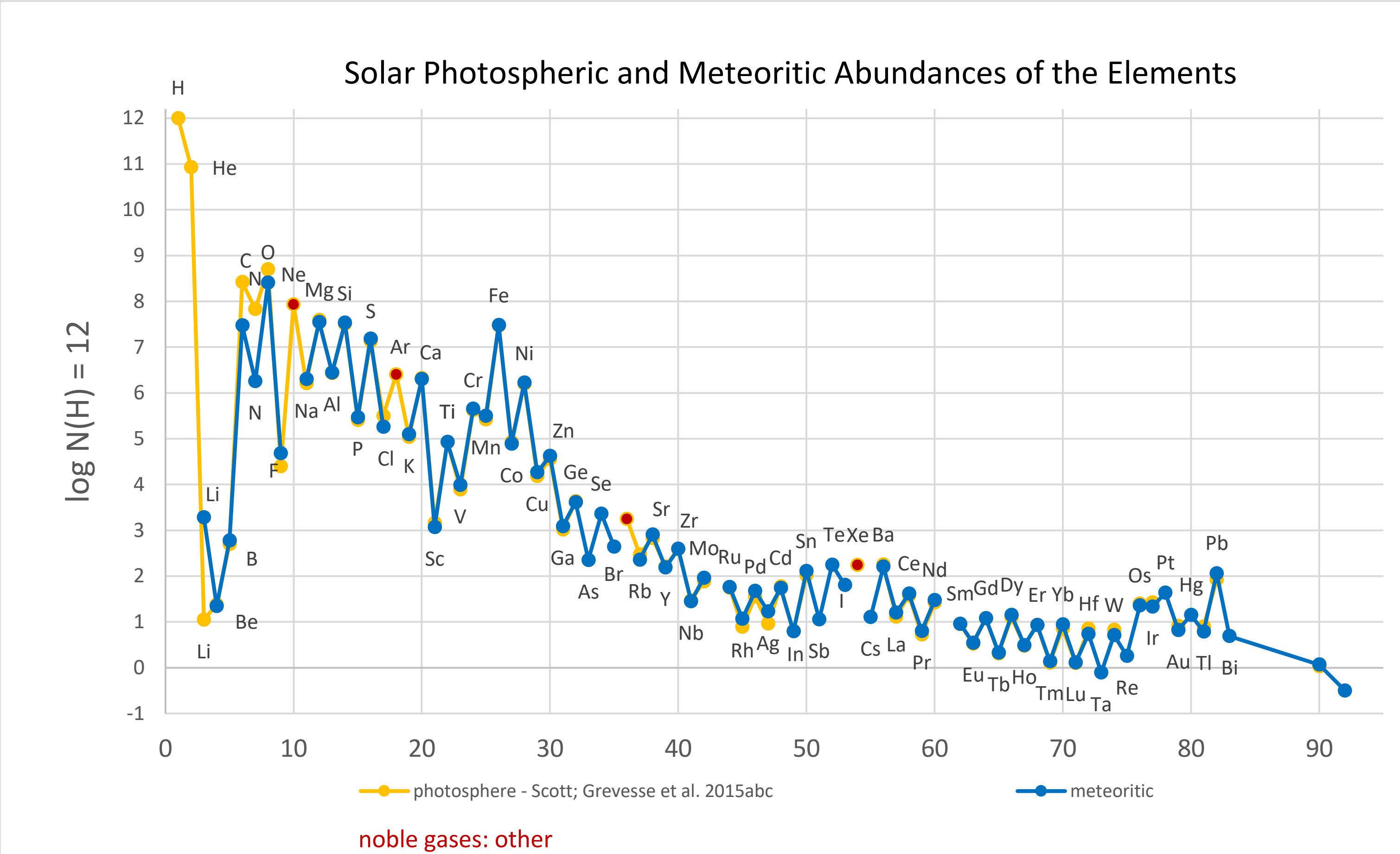
Pb



Solar Photospheric and Meteoritic Abundances of the Elements
log N(H) = 12
photosphere - Scott; Grevesse et al. 2015abc
meteoritic
noble gases: other

Outlook

The solar system abundances of many elements agree within 0.1 dex in meteoritic and photospheric values but large uncertainties remain for several elements.

3D models introduce a larger spread between meteoritic and photospheric data

Re-analyses for several elements are needed

- CI-chondrites Be, Hg, As, Sb, Sn, Te, F, Cl, Br, I, Nb, Ta
  evaluation of analysis methods (example S)
  may require refinements of, or new analyses
  element host phases, natural variations (sample sizes)

- Solar photospheric abundances – C,N,O, noble gases, oxygen crisis?
Co, Mn, Rb, W, Ca, Ga, Ge, Sn, Rb, Ag, Au, W, Tm, Lu, Th, U, Hg

Sun-spot data: F & Cl recently updated, Tl, In still uncertain

Are differences between solar photosphere and CI-chondrite data real or the result of analytical difficulties?

Isotopic compositions of the elements are mainly taken from terrestrial rocks and meteorites – are these the same in the Sun? SW?

Fin