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Heavy metals in hot white dwarf stars

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Stellar evolution: neutron-capture nucleosynthesis

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Summary

Introduction

Chemical evolution of the Universe is driven by nucleosynthesis of chemical elements in stars

Evolved stars return a significant fraction of their mass (up to 95%) to the interstellar matter (stellar winds, supernova explosions)

This material is enriched with heavy elements produced in the stellar interior and dredged up to the surface by convective motions

For quantitative modeling of Galactic chemical evolution we must know: The *stellar yields* of chemical elements, i.e., how much elements are produced by which stars?

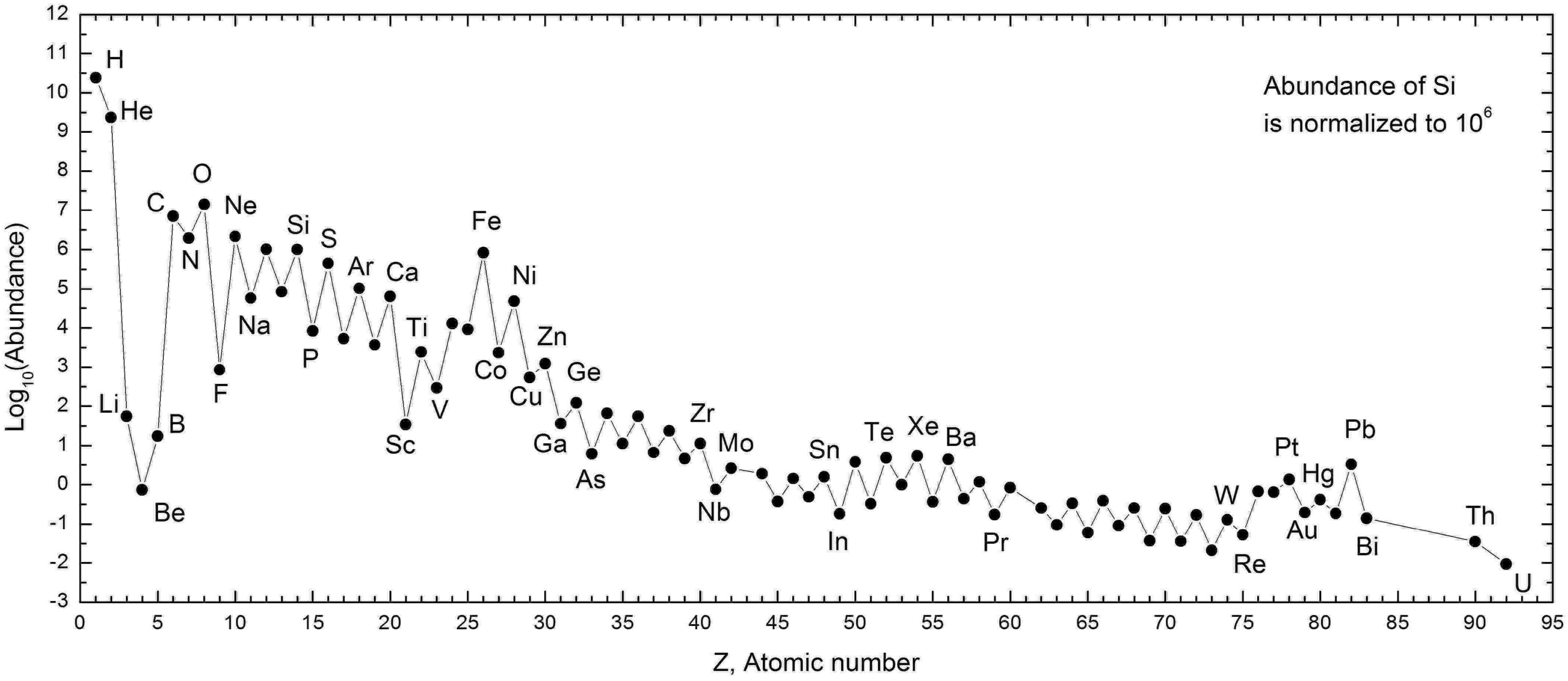
Metal yields are computed with stellar evolution models, but uncertainties in numerical modeling

Biggest problem: Mixing processes (convection) and some nuclear reaction rates

Only solution: Compare surface abundances, predicted by evolution models, with observations, i.e.:

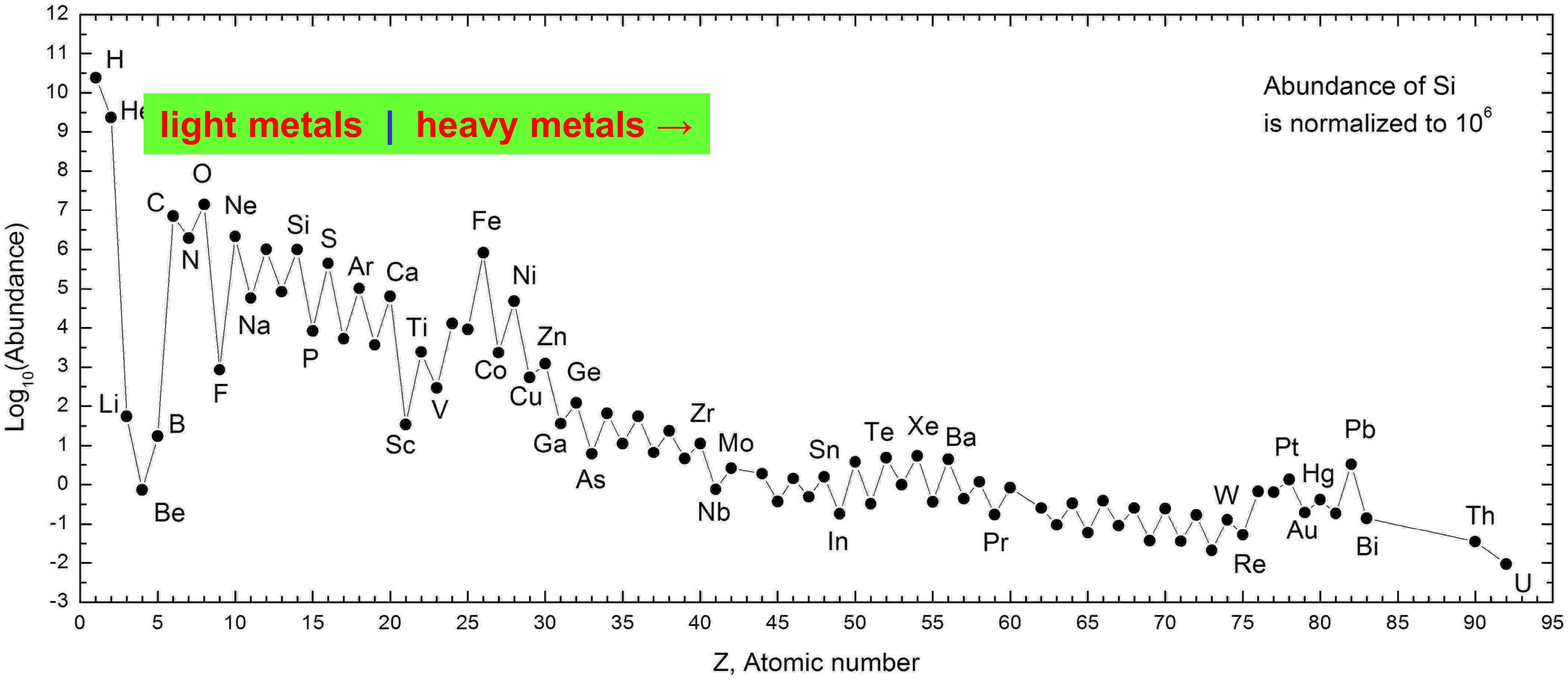
Quantitative spectroscopy is the only possibility to “calibrate“ stellar models

The “standard“: element abundances in the Sun



wikipedia

The “standard“: element abundances in the Sun

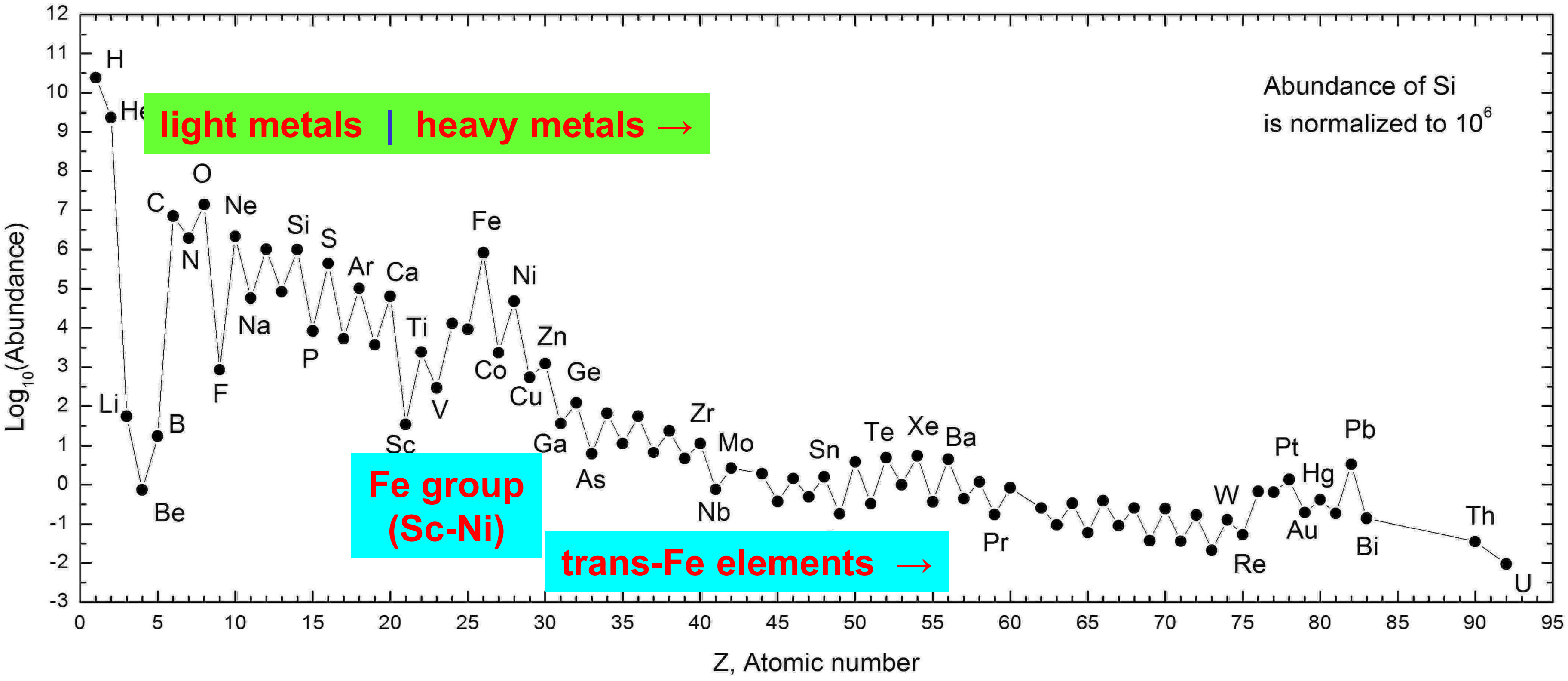


light metals | heavy metals →

Abundance of Si is normalized to 10^6

wikipedia

The “standard“: element abundances in the Sun



light metals | heavy metals →

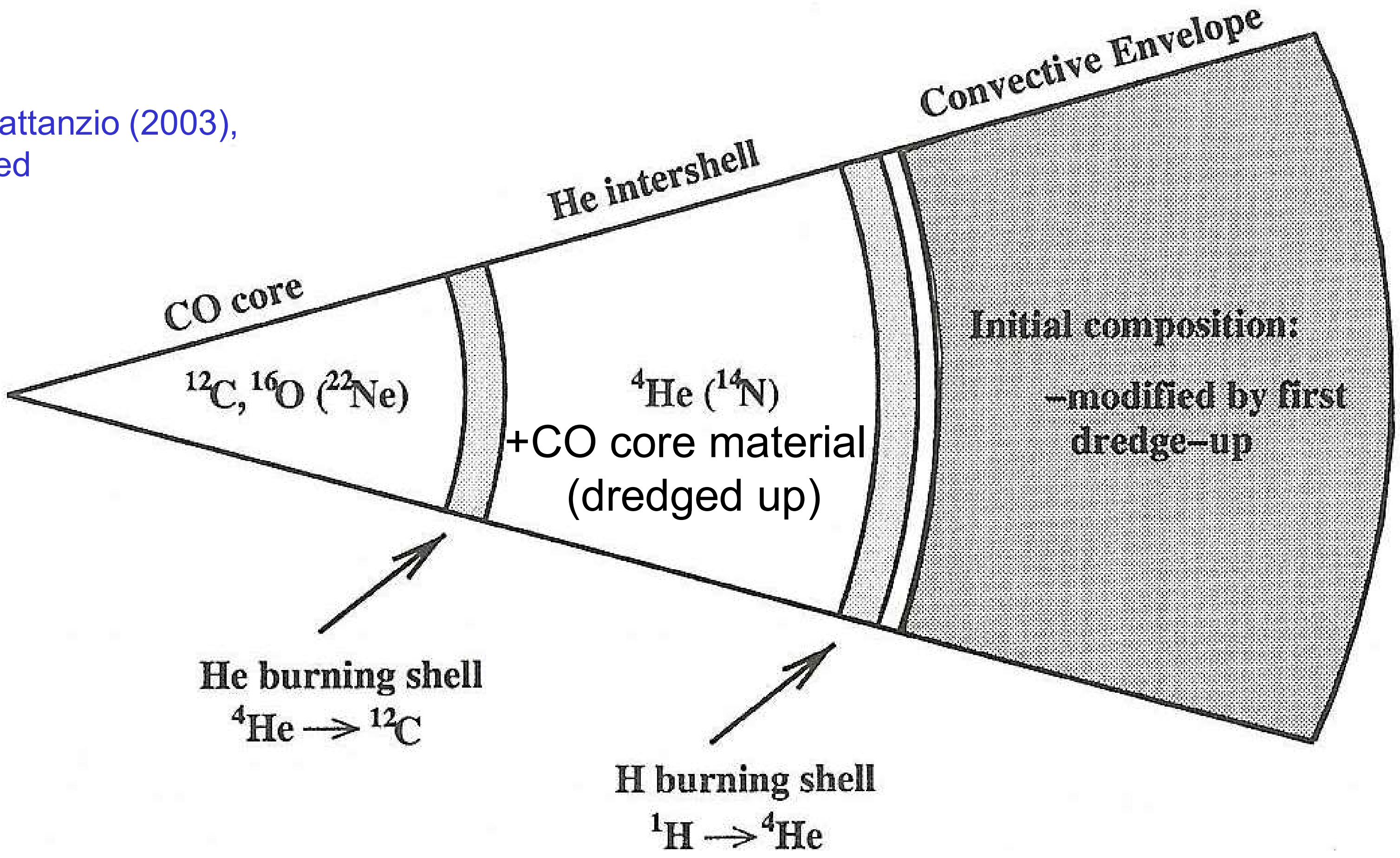
Fe group (Sc-Ni)

trans-Fe elements →

wikipedia

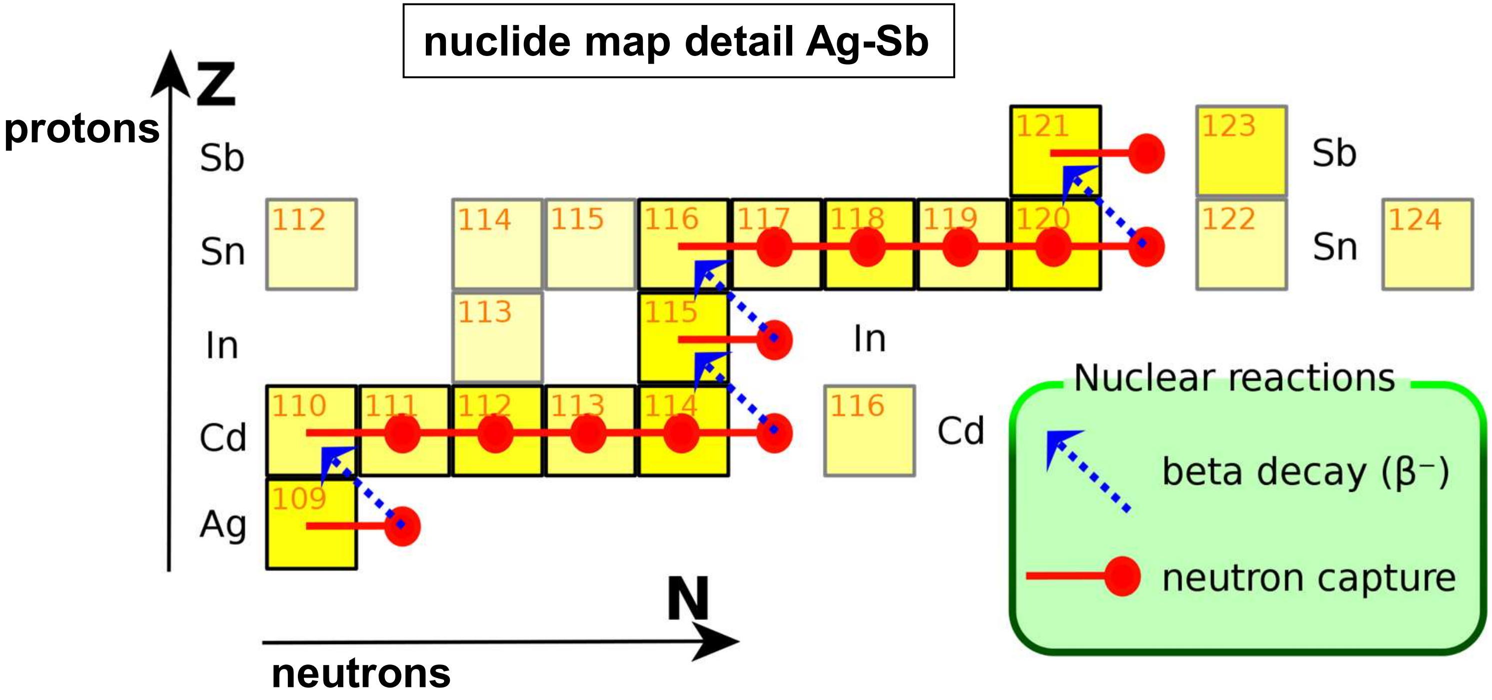
Red giant star: interior structure

from Lattanzio (2003), modified



All stars < 8 solar masses end their life with cessation of H and He burning, becoming white dwarfs.

Heavy elements in stars produced by
- nuclear fusion (up to iron)
- neutron-captures on heavy nuclei



wikipedia

n-captures in red giants: "s-process"

s = slow, i.e., time between n-captures long compared to half-life for beta-decay

s-process in red giants

Main neutron source is reaction starting from ^{12}C nuclei (from He-burning shell):

$^{12}C(p,\gamma)^{13}N(\beta^{+}\nu)^{13}C(\alpha,n)^{16}O$ protons mixed down from H envelope

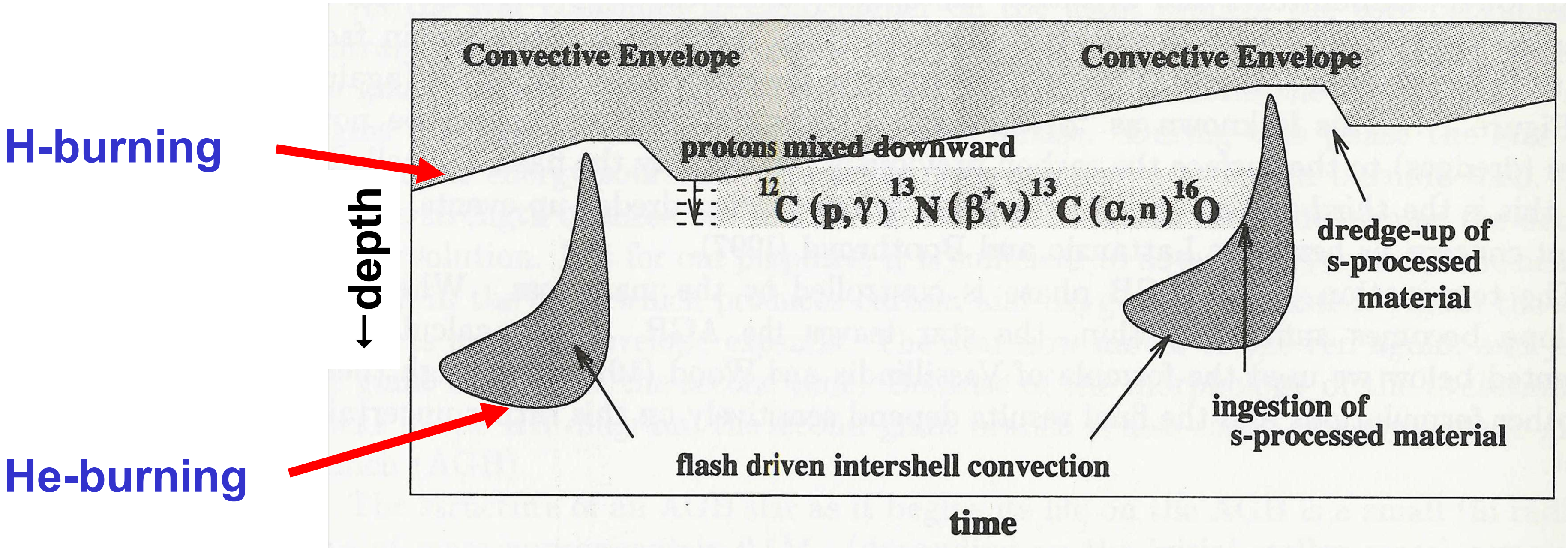


Figure 2. Making *s*-process elements during AGB evolution.

Lattanzio 1998

Products of s-process nucleosynthesis in intershell region are not directly observable; hidden below massive, convective hydrogen-rich stellar envelope

Dredge-up (convection) of s-processed material to the surface of red giants; spectroscopically detectable

But: difficult interpretation, because additional burning and mixing processes in the convective H envelope blurr the picture

Fortunately: Nature, in some cases, allows a direct view onto the processed material: hydrogen-deficient (pre-) white dwarfs have lost their hydrogen-envelope

Hydrogen-deficient (pre-) white dwarfs

Ca. 20% of all (pre-) white dwarfs are free of hydrogen

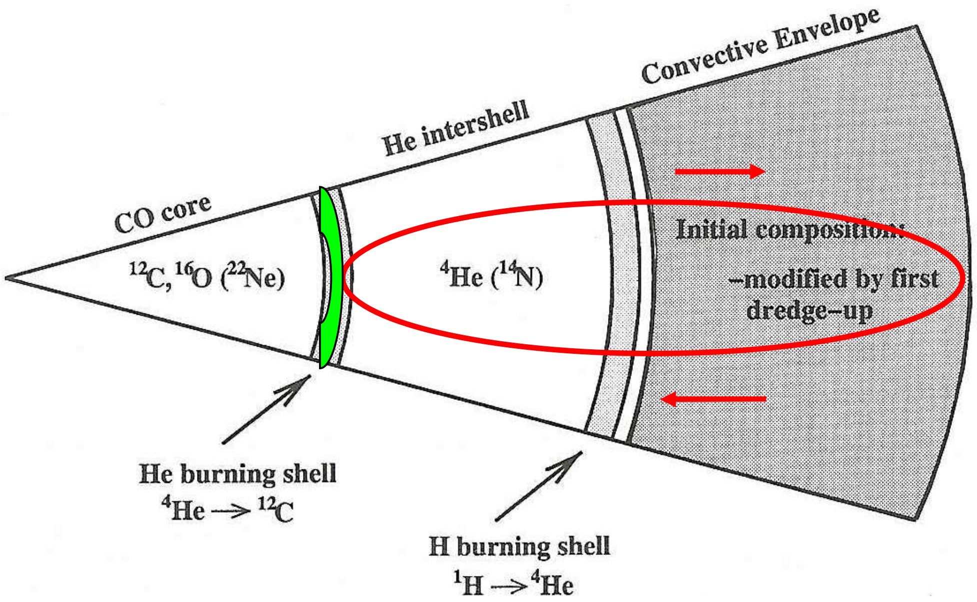
Atmospheres dominated by He=60%, C=30%, O=10% (mass fractions)

= chemistry of material between H and He burning shells in red giants (intershell abundances)

Origin: these stars were already white dwarfs, but re-ignite He-fusion, “helium-shell flash”, “born-again” stars

Consequence: flash-induced envelope convection

H is ingested and burned, He-rich intershell material lifted up



Measurement of element abundances by quantitative spectroscopic analysis

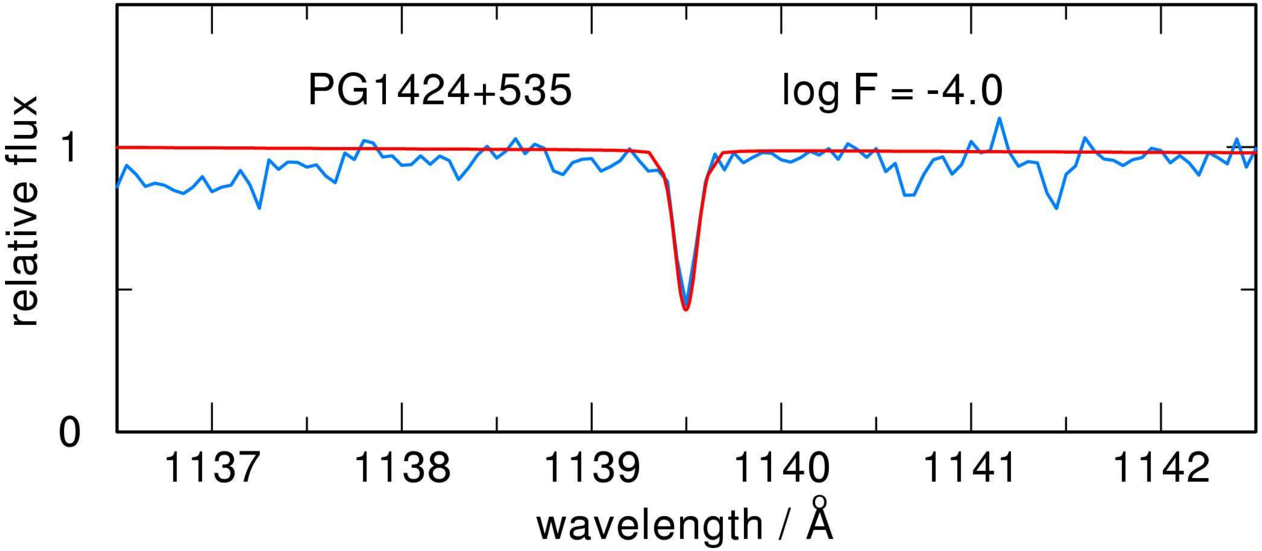
Abundances of main atmospheric constituents (He, C, O) can be determined from optical spectra

Heavy elements only accessible with ultraviolet spectroscopy (*Hubble* and *FUSE* Space Telescopes)

Model atmospheres: plane-parallel, hydrostatic, radiative equilibrium, non-local thermodynamic equilibrium

Fluorine (^{19}F)

- Interesting element, origin is unclear: formed by nucleosynthesis in red giants stars or massive stars? Or by neutrino spallation of ^{20}Ne in supernovae?
- Interesting to know intershell abundance of F, use H-deficient stars as "probes"
- Discovery of F V and F VI lines



fluorine overabundant by factor 200!

(Werner et al. 2005)

Trans-iron elements

Low-mass stars have produced ~50% of all elements heavier than iron in our Galaxy.

Produced by neutron captures (s process)

Large overabundances expected in hydrogen-deficient (pre-) white dwarfs

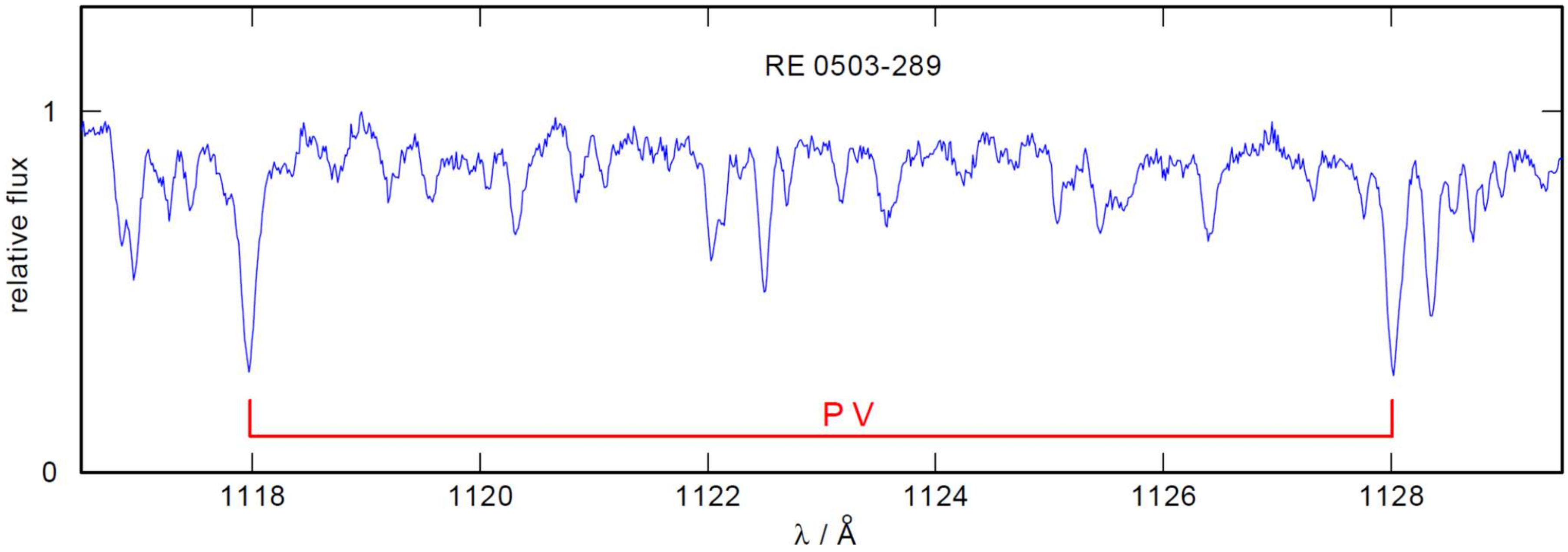
Would be interesting to find these elements, and to compare their abundances with nucleosynthesis models

Since 2012: discovery of 18 trans-iron elements in the helium-dominated white dwarf RE 0503-289

- FUSE space telescope observed UV spectra in 2000/2001

  -- Large number of unidentified spectral lines; not seen in any other white dwarf star

  -- Problem unsolved for a decade

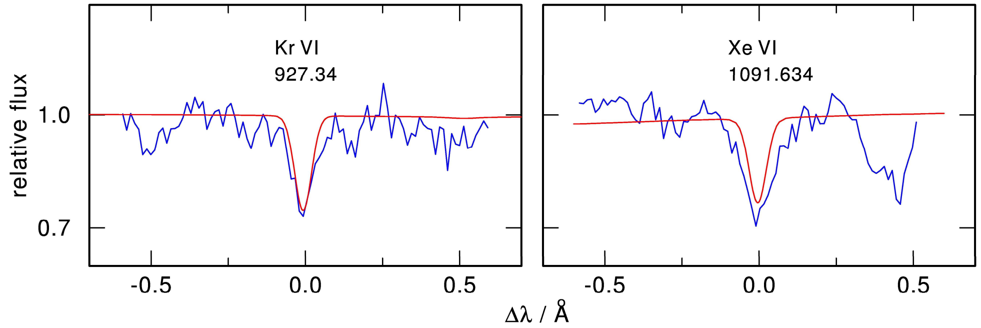


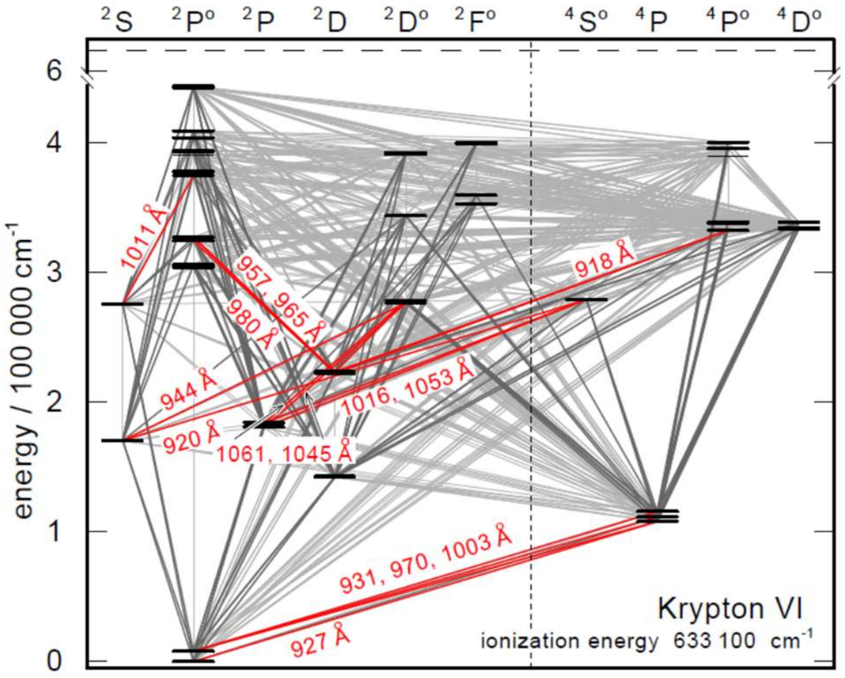
Identification of krypton und xenon

- 20 lines detected from Kr VI - VII and Xe VI - VII

- Abundance determination possible, because atomic data available (energy levels, f-values [oscillator strengths])

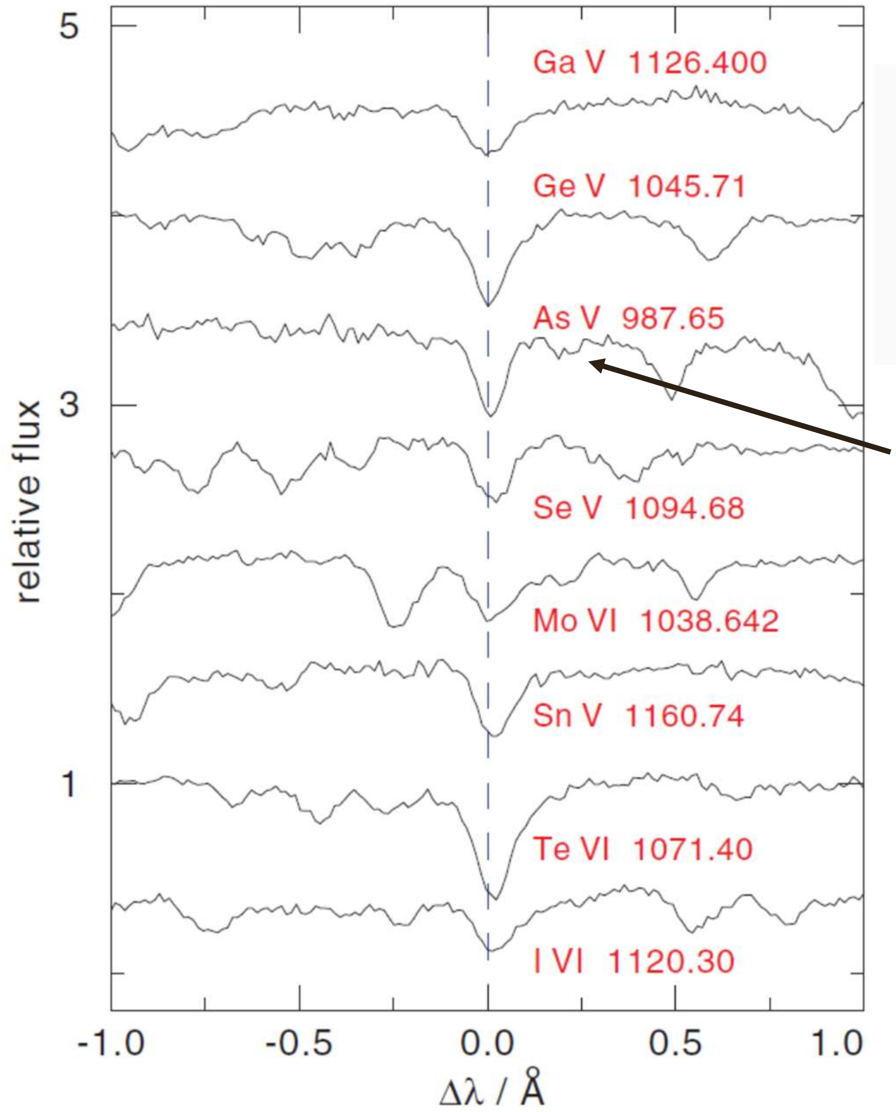
- For atomic models: all f-values required (not only those for observed lines)





Werner, Rauch, Ringat, Kruk (2012)

Identification of 18 heavy metals, highly ionised



Arrsenic!

In a dead star!!

Trans-Fe elements in RE0503-289

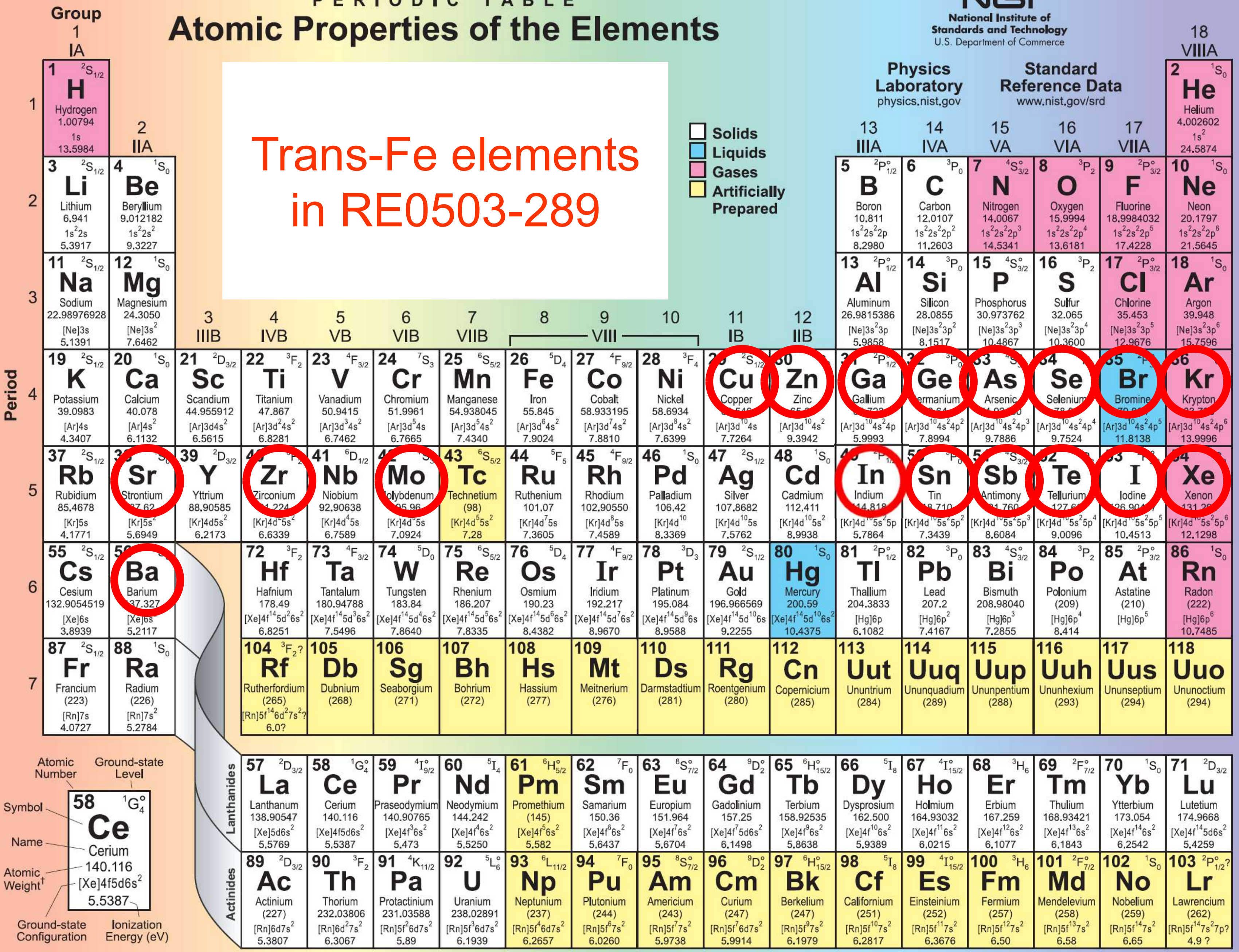
PERIODIC TABLE

Atomic Properties of the Elements

NIST
National Institute of Standards and Technology
U.S. Department of Commerce

Physics Laboratory
physics.nist.gov

Standard Reference Data
www.nist.gov/srd



☐ Solids
🟦 Liquids
🟪 Gases
🟨 Artificially Prepared

Period	Group 1 IA	2 IIA	3 IIIB	4 IVB	5 VB	6 VIB	7 VIIB	8 VIII	9 VIII	10 VIII	11 IB	12 IIB	13 IIIA	14 IVA	15 VA	16 VIA	17 VIIA	18 VIIIA
1	1 $^2S_{1/2}$ **H** Hydrogen 1.00794 $1s$ 13.5984																	2 $^1S_0$ **He** Helium 4.002602 $1s^2$ 24.5874
2	3 $^2S_{1/2}$ **Li** Lithium 6.941 $1s^22s$ 5.3917	4 $^1S_0$ **Be** Beryllium 9.012182 $1s^22s^2$ 9.3227											5 $^2P^°_{1/2}$ **B** Boron 10.811 $1s^22s^22p$ 8.2980	6 $^3P_0$ **C** Carbon 12.0107 $1s^22s^22p^2$ 11.2603	7 $^4S^°_{3/2}$ **N** Nitrogen 14.0067 $1s^22s^22p^3$ 14.5341	8 $^3P_2$ **O** Oxygen 15.9994 $1s^22s^22p^4$ 13.6181	9 $^2P^°_{3/2}$ **F** Fluorine 18.9984032 $1s^22s^22p^5$ 17.4228	10 $^1S_0$ **Ne** Neon 20.1797 $1s^22s^22p^6$ 21.5645
3	11 $^2S_{1/2}$ **Na** Sodium 22.98976928 $[Ne]3s$ 5.1391	12 $^1S_0$ **Mg** Magnesium 24.3050 $[Ne]3s^2$ 7.6462											13 $^2P^°_{1/2}$ **Al** Aluminum 26.9815386 $[Ne]3s^23p$ 5.9858	14 $^3P_0$ **Si** Silicon 28.0855 $[Ne]3s^23p^2$ 8.1517	15 $^4S^°_{3/2}$ **P** Phosphorus 30.973762 $[Ne]3s^23p^3$ 10.4867	16 $^3P_2$ **S** Sulfur 32.065 $[Ne]3s^23p^4$ 10.3600	17 $^2P^°_{3/2}$ **Cl** Chlorine 35.453 $[Ne]3s^23p^5$ 12.9676	18 $^1S_0$ **Ar** Argon 39.948 $[Ne]3s^23p^6$ 15.7596
4	19 $^2S_{1/2}$ **K** Potassium 39.0983 $[Ar]4s$ 4.3407	20 $^1S_0$ **Ca** Calcium 40.078 $[Ar]4s^2$ 6.1132	21 $^2D_{3/2}$ **Sc** Scandium 44.955912 $[Ar]3d4s^2$ 6.5615	22 $^3F_2$ **Ti** Titanium 47.867 $[Ar]3d^24s^2$ 6.8281	23 $^4F_{3/2}$ **V** Vanadium 50.9415 $[Ar]3d^34s^2$ 6.7462	24 $^7S_3$ **Cr** Chromium 51.9961 $[Ar]3d^54s$ 6.7665	25 $^6S_{5/2}$ **Mn** Manganese 54.938045 $[Ar]3d^54s^2$ 7.4340	26 $^5D_4$ **Fe** Iron 55.845 $[Ar]3d^64s^2$ 7.9024	27 $^4F_{9/2}$ **Co** Cobalt 58.933195 $[Ar]3d^74s^2$ 7.8810	28 $^3F_4$ **Ni** Nickel 58.6934 $[Ar]3d^84s^2$ 7.6399	29 $^2S_{1/2}$ **Cu** Copper 63.546 $[Ar]3d^{10}4s$ 7.7264	30 $^1S_0$ **Zn** Zinc 65.38 $[Ar]3d^{10}4s^2$ 9.3942	31 $^2P^°_{1/2}$ **Ga** Gallium 69.723 $[Ar]3d^{10}4s^24p$ 5.9993	32 $^3P_0$ **Ge** Germanium 72.64 $[Ar]3d^{10}4s^24p^2$ 7.8994	33 $^4S^°_{3/2}$ **As** Arsenic 74.92160 $[Ar]3d^{10}4s^24p^3$ 9.7886	34 $^3P_2$ **Se** Selenium 78.96 $[Ar]3d^{10}4s^24p^4$ 9.7524	35 $^2P^°_{3/2}$ **Br** Bromine 79.904 $[Ar]3d^{10}4s^24p^5$ 11.8138	36 $^1S_0$ **Kr** Krypton 83.798 $[Ar]3d^{10}4s^24p^6$ 13.9996
5	37 $^2S_{1/2}$ **Rb** Rubidium 85.4678 $[Kr]5s$ 4.1771	38 $^1S_0$ **Sr** Strontium 87.62 $[Kr]5s^2$ 5.6949	39 $^2D_{3/2}$ **Y** Yttrium 88.90585 $[Kr]4d5s^2$ 6.2173	40 $^3F_2$ **Zr** Zirconium 91.224 $[Kr]4d^25s^2$ 6.6339	41 $^6D_{1/2}$ **Nb** Niobium 92.90638 $[Kr]4d^45s$ 6.7589	42 $^7S_3$ **Mo** Molybdenum 95.96 $[Kr]4d^55s$ 7.0924	43 $^6S_{5/2}$ **Tc** Technetium (98) $[Kr]4d^55s^2$ 7.28	44 $^5F_5$ **Ru** Ruthenium 101.07 $[Kr]4d^75s$ 7.3605	45 $^4F_{9/2}$ **Rh** Rhodium 102.90550 $[Kr]4d^85s$ 7.4589	46 $^1S_0$ **Pd** Palladium 106.42 $[Kr]4d^{10}$ 8.3369	47 $^2S_{1/2}$ **Ag** Silver 107.8682 $[Kr]4d^{10}5s$ 7.5762	48 $^1S_0$ **Cd** Cadmium 112.411 $[Kr]4d^{10}5s^2$ 8.9938	49 $^2P^°_{1/2}$ **In** Indium 114.818 $[Kr]4d^{10}5s^25p$ 5.7864	50 $^3P_0$ **Sn** Tin 118.710 $[Kr]4d^{10}5s^25p^2$ 7.3439	51 $^4S^°_{3/2}$ **Sb** Antimony 121.760 $[Kr]4d^{10}5s^25p^3$ 8.6084	52 $^3P_2$ **Te** Tellurium 127.60 $[Kr]4d^{10}5s^25p^4$ 9.0096	53 $^2P^°_{3/2}$ **I** Iodine 126.90447 $[Kr]4d^{10}5s^25p^5$ 10.4513	54 $^1S_0$ **Xe** Xenon 131.293 $[Kr]4d^{10}5s^25p^6$ 12.1298
6	55 $^2S_{1/2}$ **Cs** Cesium 132.9054519 $[Xe]6s$ 3.8939	56 $^1S_0$ **Ba** Barium 137.327 $[Xe]6s^2$ 5.2117		72 $^3F_2$ **Hf** Hafnium 178.49 $[Xe]4f^{14}5d^26s^2$ 6.8251	73 $^4F_{3/2}$ **Ta** Tantalum 180.94788 $[Xe]4f^{14}5d^36s^2$ 7.5496	74 $^5D_0$ **W** Tungsten 183.84 $[Xe]4f^{14}5d^46s^2$ 7.8640	75 $^6S_{5/2}$ **Re** Rhenium 186.207 $[Xe]4f^{14}5d^56s^2$ 7.8335	76 $^5D_4$ **Os** Osmium 190.23 $[Xe]4f^{14}5d^66s^2$ 8.4382	77 $^4F_{9/2}$ **Ir** Iridium 192.217 $[Xe]4f^{14}5d^76s^2$ 8.9670	78 $^3D_3$ **Pt** Platinum 195.084 $[Xe]4f^{14}5d^96s$ 8.9588	79 $^2S_{1/2}$ **Au** Gold 196.966569 $[Xe]4f^{14}5d^{10}6s$ 9.2255	80 $^1S_0$ **Hg** Mercury 200.59 $[Xe]4f^{14}5d^{10}6s^2$ 10.4375	81 $^2P^°_{1/2}$ **Tl** Thallium 204.3833 $[Hg]6p$ 6.1082	82 $^3P_0$ **Pb** Lead 207.2 $[Hg]6p^2$ 7.4167	83 $^4S^°_{3/2}$ **Bi** Bismuth 208.98040 $[Hg]6p^3$ 7.2855	84 $^3P_2$ **Po** Polonium (209) $[Hg]6p^4$ 8.414	85 $^2P^°_{3/2}$ **At** Astatine (210) $[Hg]6p^5$	86 $^1S_0$ **Rn** Radon (222) $[Hg]6p^6$ 10.7485
7	87 $^2S_{1/2}$ **Fr** Francium (223) $[Rn]7s$ 4.0727	88 $^1S_0$ **Ra** Radium (226) $[Rn]7s^2$ 5.2784		104 $^3F_2$? **Rf** Rutherfordium (265) $[Rn]5f^{14}6d^27s^2$? 6.0?	105 **Db** Dubnium (268)	106 **Sg** Seaborgium (271)	107 **Bh** Bohrium (272)	108 **Hs** Hassium (277)	109 **Mt** Meitnerium (276)	110 **Ds** Darmstadtium (281)	111 **Rg** Roentgenium (280)	112 **Cn** Copernicium (285)	113 **Uut** Ununtrium (284)	114 **Uuq** Ununquadium (289)	115 **Uup** Ununpentium (288)	116 **Uuh** Ununhexium (293)	117 **Uus** Ununseptium (294)	118 **Uuo** Ununoctium (294)

Lanthanides	57 $^2D_{3/2}$ **La** Lanthanum 138.90547 $[Xe]5d6s^2$ 5.5769	58 $^1G^°_4$ **Ce** Cerium 140.116 $[Xe]4f5d6s^2$ 5.5387	59 $^4I^°_{9/2}$ **Pr** Praseodymium 140.90765 $[Xe]4f^36s^2$ 5.473	60 $^5I_4$ **Nd** Neodymium 144.242 $[Xe]4f^46s^2$ 5.5250	61 $^6H^°_{5/2}$ **Pm** Promethium (145) $[Xe]4f^56s^2$ 5.582	62 $^7F_0$ **Sm** Samarium 150.36 $[Xe]4f^66s^2$ 5.6437	63 $^8S^°_{7/2}$ **Eu** Europium 151.964 $[Xe]4f^76s^2$ 5.6704	64 $^9D^°_2$ **Gd** Gadolinium 157.25 $[Xe]4f^75d6s^2$ 6.1498	65 $^6H^°_{15/2}$ **Tb** Terbium 158.92535 $[Xe]4f^96s^2$ 5.8638	66 $^5I_8$ **Dy** Dysprosium 162.500 $[Xe]4f^{10}6s^2$ 5.9389	67 $^4I^°_{15/2}$ **Ho** Holmium 164.93032 $[Xe]4f^{11}6s^2$ 6.0215	68 $^3H_6$ **Er** Erbium 167.259 $[Xe]4f^{12}6s^2$ 6.1077	69 $^2F^°_{7/2}$ **Tm** Thulium 168.93421 $[Xe]4f^{13}6s^2$ 6.1843	70 $^1S_0$ **Yb** Ytterbium 173.054 $[Xe]4f^{14}6s^2$ 6.2542	71 $^2D_{3/2}$ **Lu** Lutetium 174.9668 $[Xe]4f^{14}5d6s^2$ 5.4259
Actinides	89 $^2D_{3/2}$ **Ac** Actinium (227) $[Rn]6d7s^2$ 5.3807	90 $^3F_2$ **Th** Thorium 232.03806 $[Rn]6d^27s^2$ 6.3067	91 $^4K_{11/2}$ **Pa** Protactinium 231.03588 $[Rn]5f^26d7s^2$ 5.89	92 $^5L^°_6$ **U** Uranium 238.02891 $[Rn]5f^36d7s^2$ 6.1939	93 $^6L_{11/2}$ **Np** Neptunium (237) $[Rn]5f^46d7s^2$ 6.2657	94 $^7F_0$ **Pu** Plutonium (244) $[Rn]5f^67s^2$ 6.0260	95 $^8S^°_{7/2}$ **Am** Americium (243) $[Rn]5f^77s^2$ 5.9738	96 $^9D^°_2$ **Cm** Curium (247) $[Rn]5f^76d7s^2$ 5.9914	97 $^6H^°_{15/2}$ **Bk** Berkelium (247) $[Rn]5f^97s^2$ 6.1979	98 $^5I_8$ **Cf** Californium (251) $[Rn]5f^{10}7s^2$ 6.2817	99 $^4I^°_{15/2}$ **Es** Einsteinium (252) $[Rn]5f^{11}7s^2$ 6.3676	100 $^3H_6$ **Fm** Fermium (257) $[Rn]5f^{12}7s^2$ 6.50	101 $^2F^°_{7/2}$ **Md** Mendelevium (258) $[Rn]5f^{13}7s^2$ 6.58	102 $^1S_0$ **No** Nobelium (259) $[Rn]5f^{14}7s^2$ 6.65	103 $^2P^°_{1/2}$? **Lr** Lawrencium (262) $[Rn]5f^{14}7s^27p$? 4.9 ?

Atomic Number — 58
Ground-state Level — $^1G^°_4$
Symbol — **Ce**
Name — Cerium
Atomic Weight† — 140.116
Ground-state Configuration — $[Xe]4f5d6s^2$
Ionization Energy (eV) — 5.5387

†Based upon ^{12}C. () indicates the mass number of the longest-lived isotope.

For a description of the data, visit physics.nist.gov/data

NIST SP 966 (September 2010)

Abundance analysis of trans – Fe elements

Relevant ionisation stages: V – VII

Problem: lack of atomic data. The luckier cases are ions, for which energy levels are known: can compute line positions and f-values

One of these lucky cases: zinc

> 2000 f-values computed
(relativistic Hartree-Fock approach; Cowan 1981)

→ (almost) all the >100 Zn lines in RE 0503 can be matched
Rauch, Werner, Quinet, Kruk (2014)

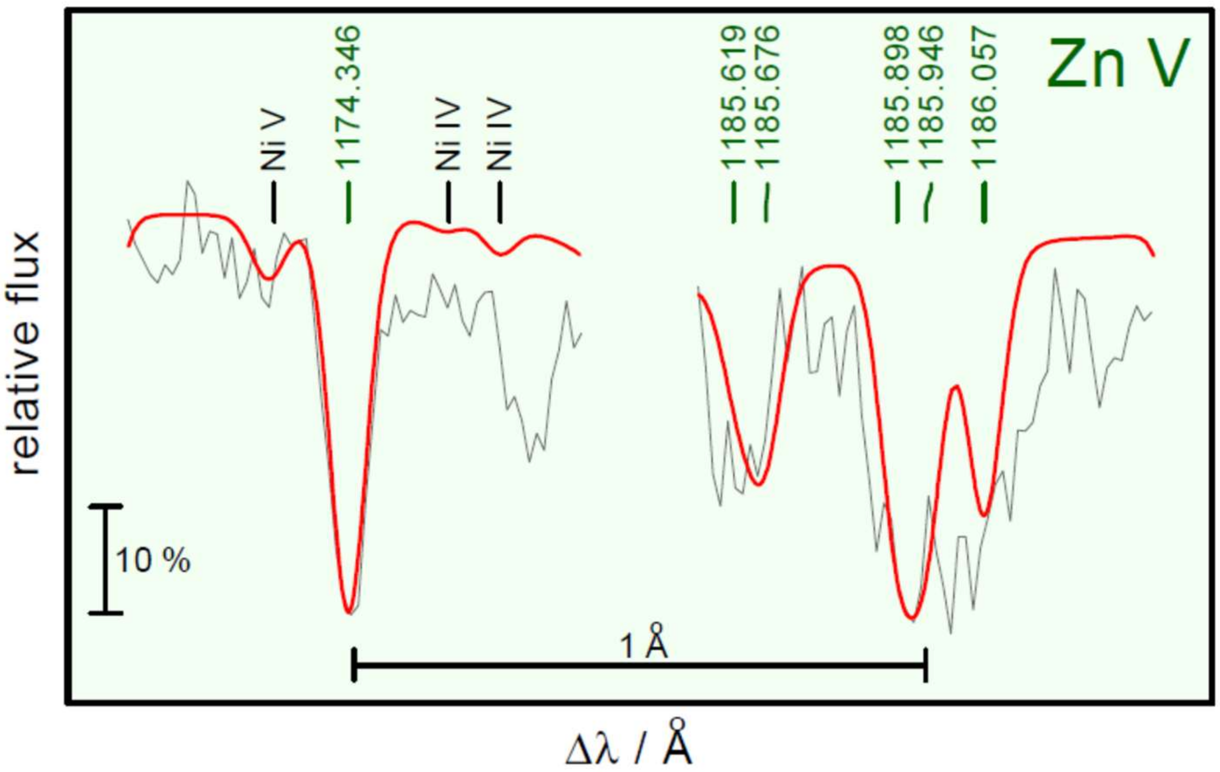
Similar work was done for copper, gallium, germanium, selenium, krypton, strontium, zirconium, molybdenum, tellurium, iodine, xenon, and barium
(Rauch et al. 2014-20)

Stellar laboratories

II. New Zn IV and Zn V oscillator strengths and their validation in the hot white dwarfs G191−B2B and RE 0503−289

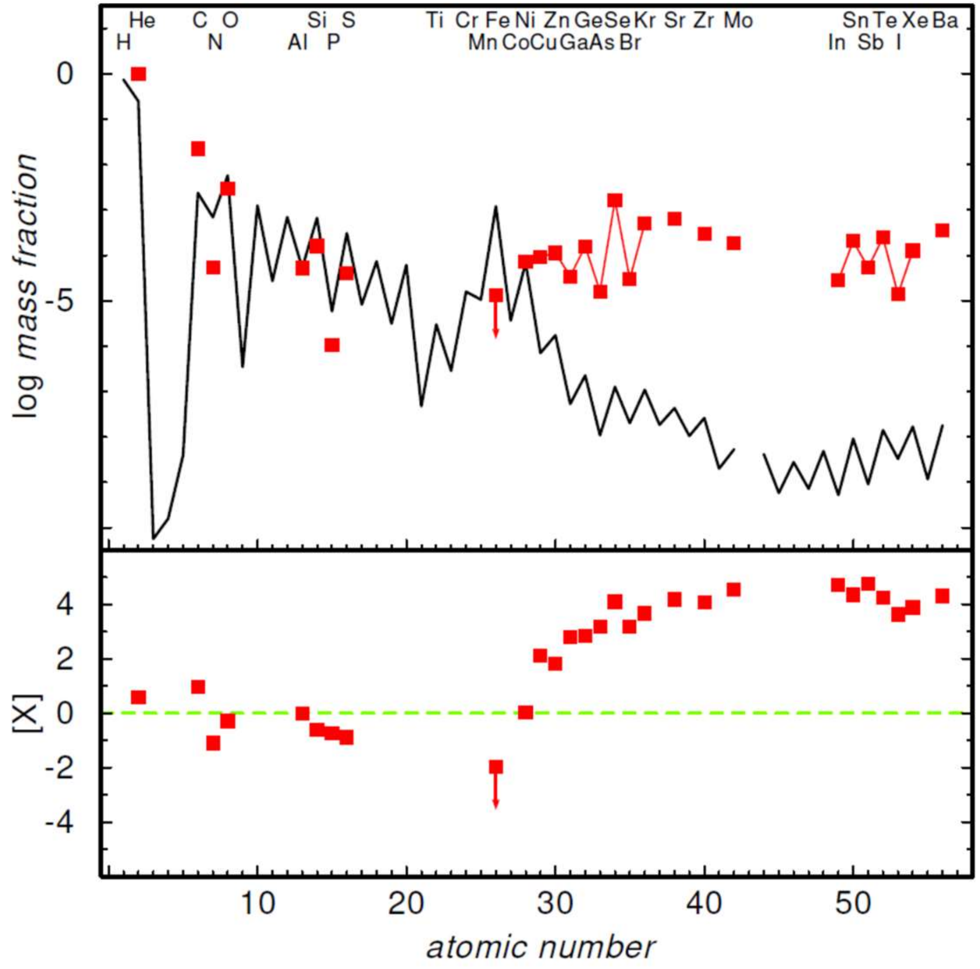
T. Rauch[1], K. Werner[1], P. Quinet[2, 3], and J. W. Kruk[4]

2014



strongest zinc lines
in RE0503-289

Trans-iron element abundances in RE 0503-289: current state



mass fractions $\sim 10^{-5} – 10^{-3}$

up to 100,000 times solar

- For other species (Cd, Ir, …): even energy levels unavailable
- Badly needed:
  laboratory measurements of line positions → level energies

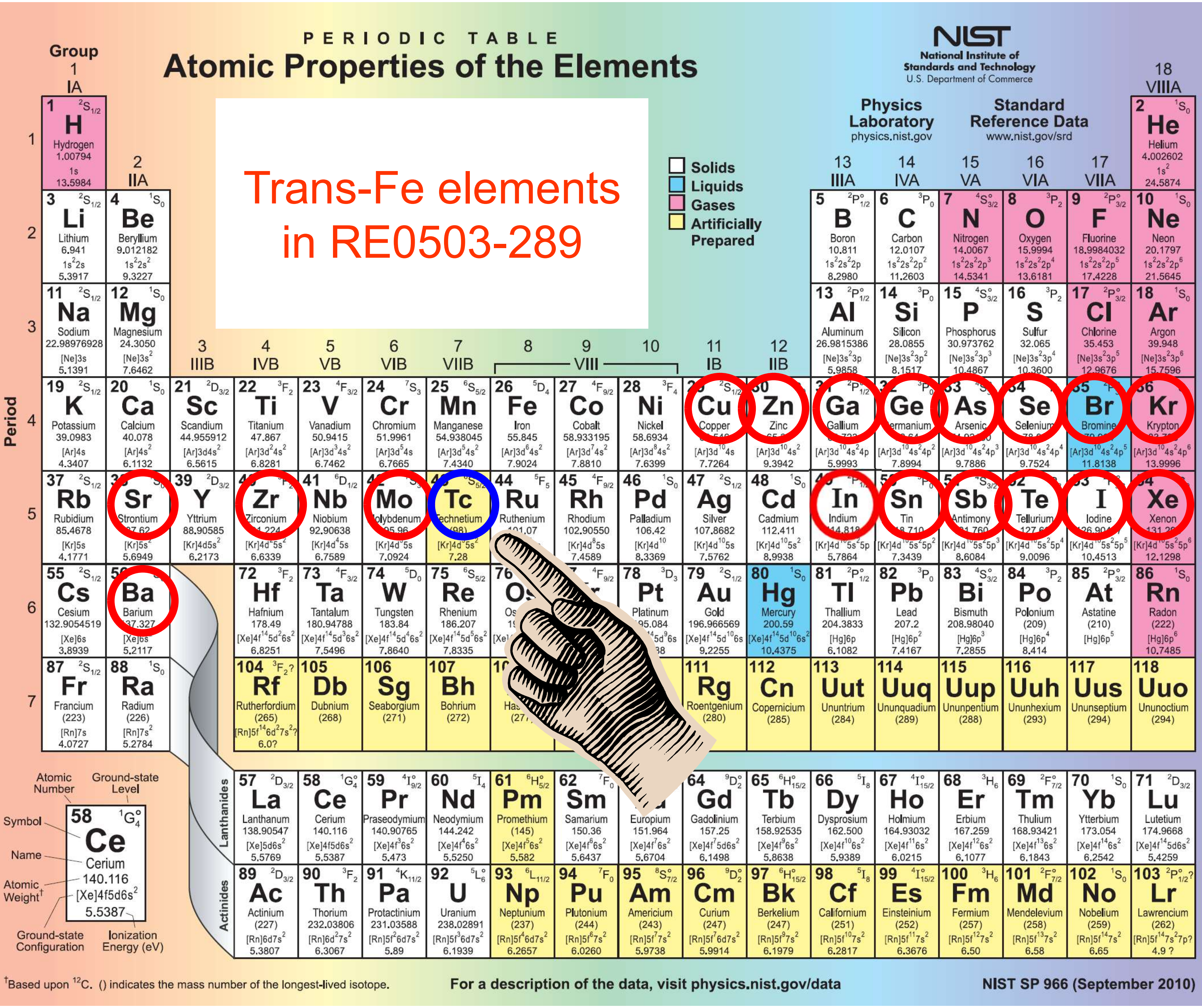
Open question:

- Why are trans-iron elements so abundant?

Could be result of:

- either s-process nucleosynthesis in red-giant phase
- or radiative pressure (“metal clouds“)
- or both

Trans-Fe elements in RE0503-289



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🟥 Gases
🟨 Artificially Prepared

Period	1 IA	2 IIA	3 IIIB	4 IVB	5 VB	6 VIB	7 VIIB	8 VIII	9 VIII	10 VIII	11 IB	12 IIB	13 IIIA	14 IVA	15 VA	16 VIA	17 VIIA	18 VIIIA
1	1 H Hydrogen																	2 He Helium
2	3 Li Lithium	4 Be Beryllium											5 B Boron	6 C Carbon	7 N Nitrogen	8 O Oxygen	9 F Fluorine	10 Ne Neon
3	11 Na Sodium	12 Mg Magnesium											13 Al Aluminum	14 Si Silicon	15 P Phosphorus	16 S Sulfur	17 Cl Chlorine	18 Ar Argon
4	19 K Potassium	20 Ca Calcium	21 Sc Scandium	22 Ti Titanium	23 V Vanadium	24 Cr Chromium	25 Mn Manganese	26 Fe Iron	27 Co Cobalt	28 Ni Nickel	Cu Copper	30 Zn Zinc	Ga Gallium	Ge Germanium	33 As Arsenic	Se Selenium	Br Bromine	Kr Krypton
5	37 Rb Rubidium	Sr Strontium	39 Y Yttrium	Zr Zirconium	41 Nb Niobium	Mo Molybdenum	Tc Technetium	44 Ru Ruthenium	45 Rh Rhodium	46 Pd Palladium	47 Ag Silver	48 Cd Cadmium	In Indium	Sn Tin	Sb Antimony	Te Tellurium	I Iodine	Xe Xenon
6	55 Cs Cesium	Ba Barium		72 Hf Hafnium	73 Ta Tantalum	74 W Tungsten	75 Re Rhenium	76 Os	[illegible]	78 Pt Platinum	79 Au Gold	80 Hg Mercury	81 Tl Thallium	82 Pb Lead	83 Bi Bismuth	84 Po Polonium	85 At Astatine	86 Rn Radon
7	87 Fr Francium	88 Ra Radium		104 Rf Rutherfordium	105 Db Dubnium	106 Sg Seaborgium	107 Bh Bohrium	[illegible]	[illegible]	[illegible]	111 Rg Roentgenium	112 Cn Copernicium	113 Uut Ununtrium	114 Uuq Ununquadium	115 Uup Ununpentium	116 Uuh Ununhexium	117 Uus Ununseptium	118 Uuo Ununoctium

Lanthanides	57 La Lanthanum	58 Ce Cerium	59 Pr Praseodymium	60 Nd Neodymium	61 Pm Promethium	62 Sm Samarium	Europium	64 Gd Gadolinium	65 Tb Terbium	66 Dy Dysprosium	67 Ho Holmium	68 Er Erbium	69 Tm Thulium	70 Yb Ytterbium	71 Lu Lutetium
Actinides	89 Ac Actinium	90 Th Thorium	91 Pa Protactinium	92 U Uranium	93 Np Neptunium	94 Pu Plutonium	95 Am Americium	96 Cm Curium	97 Bk Berkelium	98 Cf Californium	99 Es Einsteinium	100 Fm Fermium	101 Md Mendelevium	102 No Nobelium	103 Lr Lawrencium

†Based upon ^{12}C. () indicates the mass number of the longest-lived isotope.

For a description of the data, visit physics.nist.gov/data

NIST SP 966 (September 2010)

s-process path through ^{99}Tc

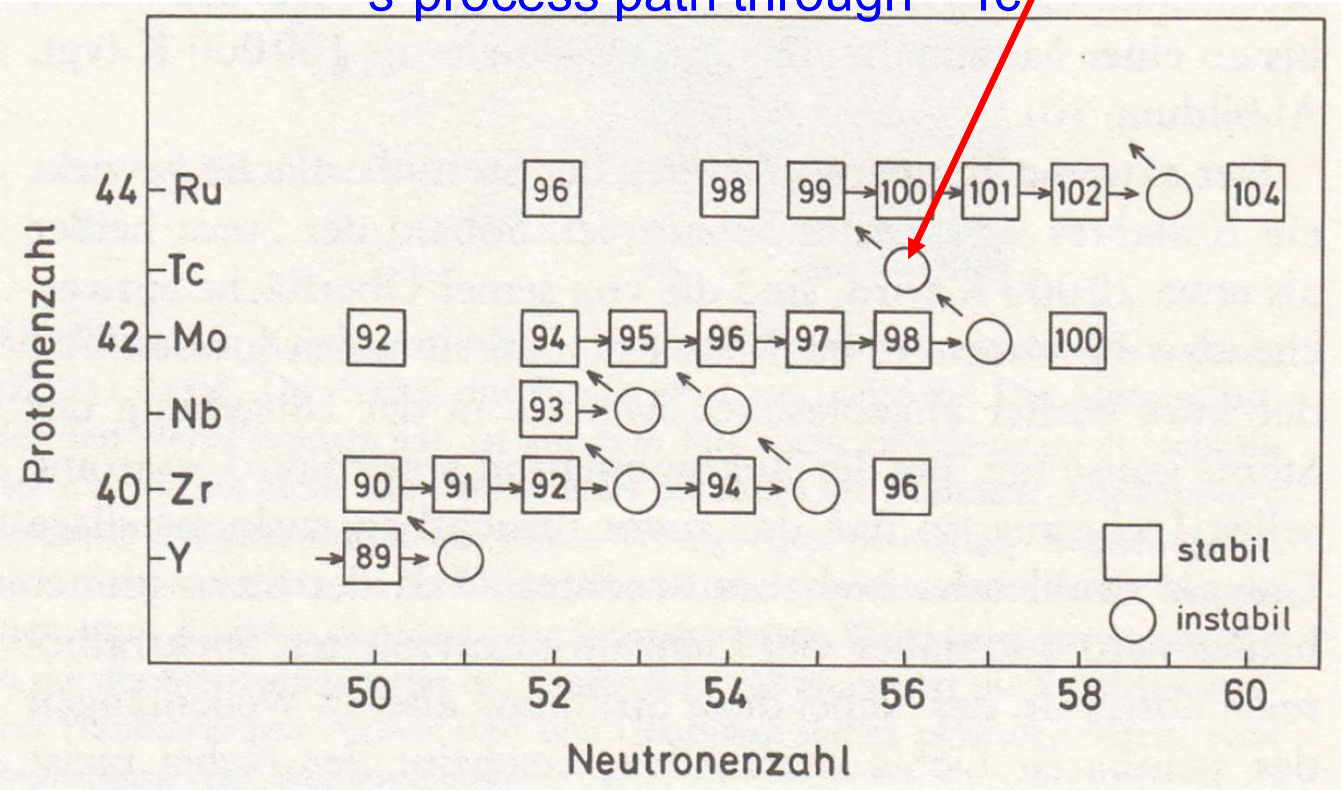


Abbildung 11: Ausschnitt des s-Prozeß-Wegs in der Nuklidkarte. Quadratisch eingezeichnete Isotope sind stabil, im Inneren der Quadrate ist deren Massenzahl angegeben. Kreisförmig eingezeichnete Kerne sind radioaktiv instabil und zerfallen in Pfeilrichtung in Kerne links oberhalb. Waagerechte Pfeile deuten Neutroneneinfänge an. Der dargestellte Ausschnitt umfaßt alle stabilen Kerne der Elemente Yttrium bis Ruthenium. Das Element Technetium besitzt keine stabilen Isotope. Das instabile Isotop ^{93}Zr hat

From: Norbert Langer “Leben und Sterben der Sterne”

Search for technetium in RE0503-289

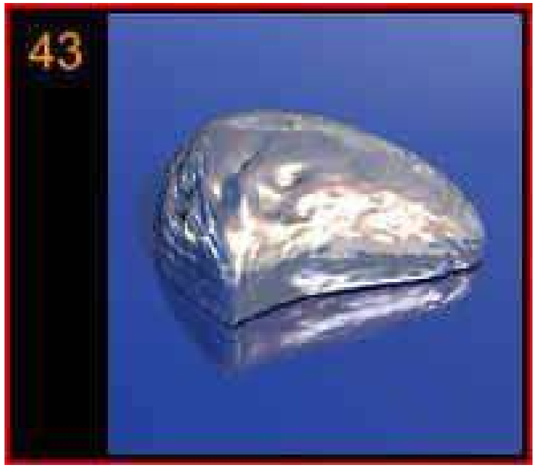
- Tc is a key element to decide whether s-process played an important role to shape the abundance pattern
- Only unstable isotopes, hence, any Tc in the WD must have been produced during previous red giant phase
  (a milestone: discovery of Tc in red giants, Merrill 1952)
- Half-live of ^{99}Tc is 210,000 yrs
- Post-red giant age of RE0503 is 650,000 yrs, i.e. ~ 3 half-lives
- Tc could still be present in the atmosphere
- Problem: Atomic data completely lacking for Tc III and higher ions

Search for technetium

- 1st step:
  Quantum mechanical computation of energy levels and f-values

  Line positions uncertain, no identification possible, but: we can check, at what abundance level Tc has detectable lines

- 2nd step:
  Observe laboratory spectra of Tc and derive energy levels



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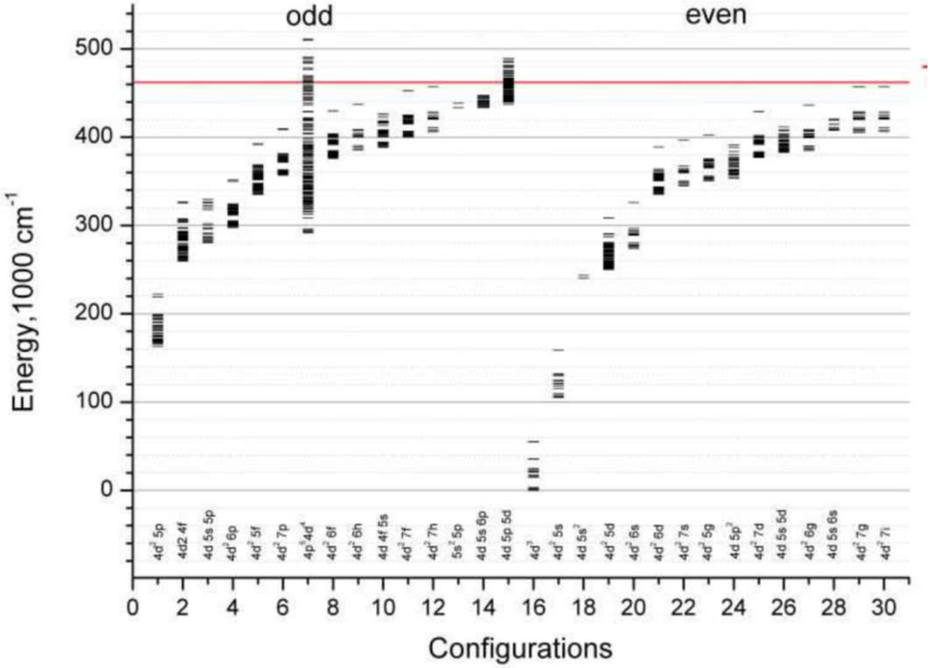
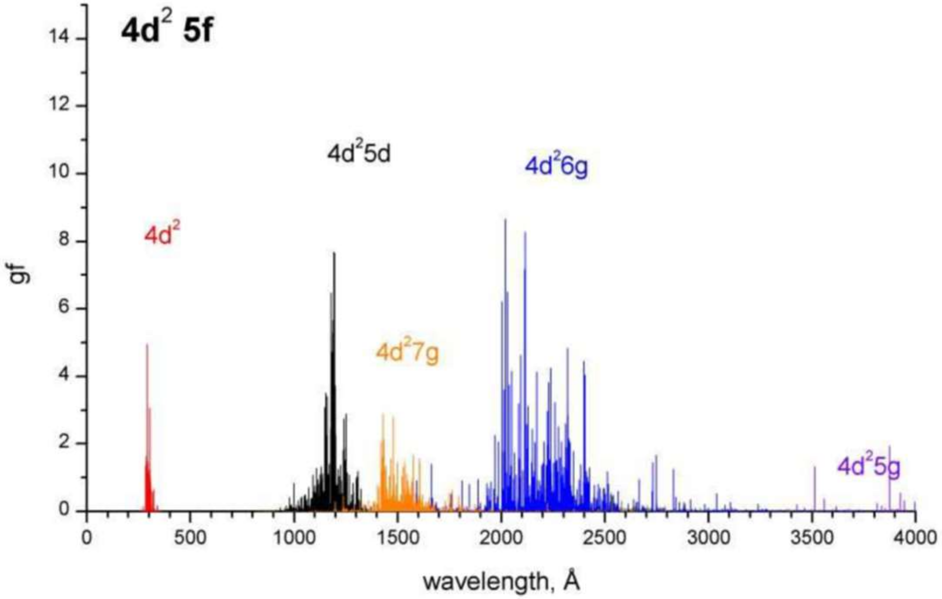
Example: computed atomic data for Tc V



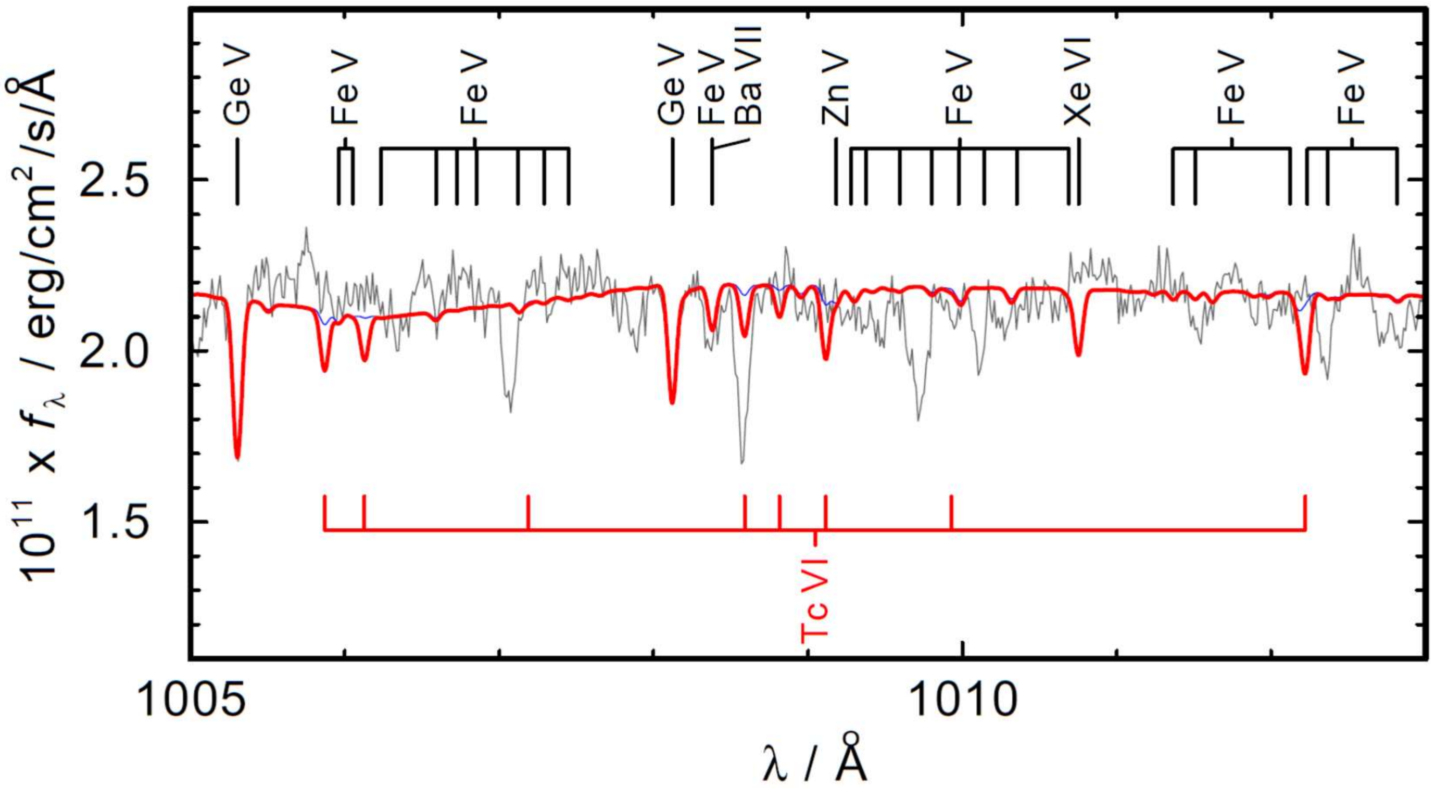


level energies

line positions and gf-values

Werner, Rauch, Kučas, Kruk (2015)

Tc VI lines in RE0503 model (Tc = 10^{-4} mass fraction)



In preparation: Laboratory spectroscopy of technetium

- Electron Beam Ion Traps (EBIT) facility at MPI for Nuclear Physics in Heidelberg to produce Tc plasma (only minute quantities of Tc required, some 10^{-12} g; radioactive!)
- 3m UV spectrograph attached (lent from BESSY, Berlin)
- MCP detector from Tübingen (flight spare of ORFEUS space telescope)
- Measurements ongoing

Electron Beam Ion Trap (EBIT)

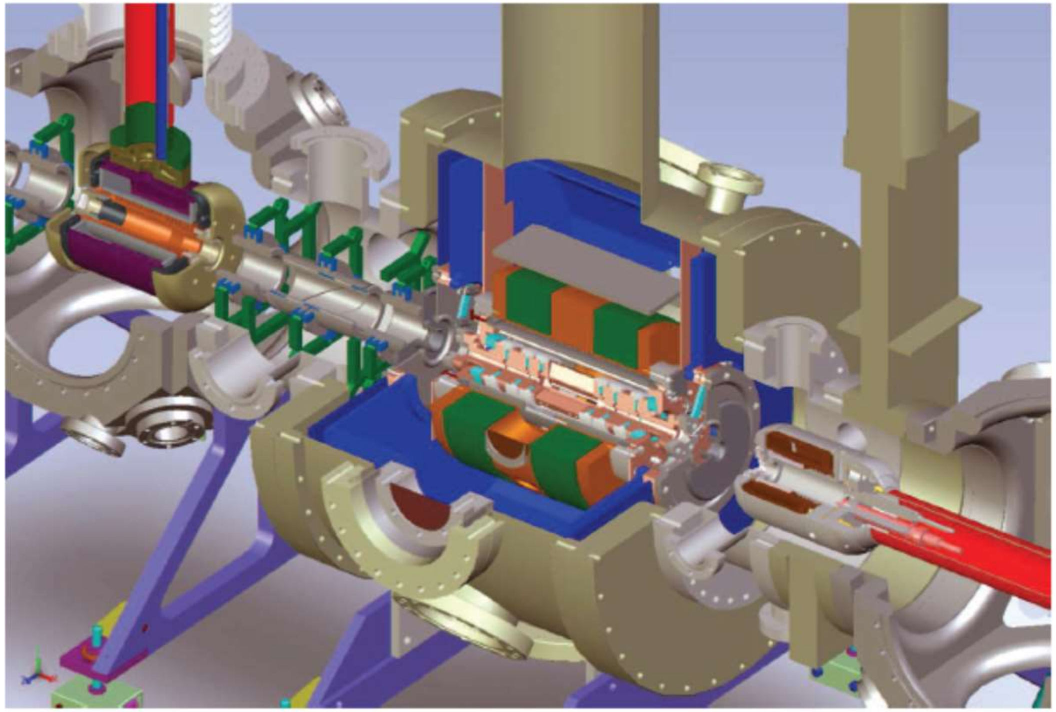


Figure 6: Section across an electron beam ion trap showing the electron gun (inside the right chamber), trap region (in the cold bore of the superconducting magnet at the center), and the electron collector (in the left chamber). The central magnetic field of 6 T focuses the axially injected electron beam to a diameter of less than 50 μm. This beam ionizes neutrals injected into the apparatus stepwise to selectable high charge states, and traps the generated ions by its negative space charge potential.

Summary:
Element abundances in hot H-deficient white dwarfs

Stellar atmospheres mainly composed of He,C,O: Ashes of H- and He-burning, mixed up by final He-shell ignition

We indeed see the direct outcome of nucleosynthesis that was at work in previous phases of stellar evolution (red giant).

The observed element abundances are hard tests for stellar models and predicted *metal yields*.

Light metals (up to iron): Abundances in accordance with models

Heavy metals (trans-iron elements): new territory. Atomic data lacking.
Laboratory plasma spectroscopy in preparation.

Heavy metals (trans-iron elements): new territory. Atomic data lacking. Laboratory plasma spectroscopy in preparation.

Díky za pozornost !