2015.2.13.
京大基研

コンパクト連星合体からの重力波・電磁波放射とその周辺領域

金属欠乏星の観測

国立天文台
青木和光

金属欠乏星の観測

- 元素組成測定の実際
  - 元素組成とスペクトル線
  - 太陽系組成
  - 測定誤差
- r-プロセスへの観測的制限
  - 個々の星の組成パターン
  - 中性子捕獲元素 (重元素) と軽元素
  - 元素組成比の分散
  - 矮小銀河
- 金属欠乏星観測の今後

Definition

- Chemical abundance：abundance ratio with respect to H

  $\log \varepsilon(X)$ or $\log A(X) = \log(X/H) + 12$

  ex. $Fe/H=10^{-4.5}$ → $\log \varepsilon(Fe)=7.5$

  $[X/Y] = \log(X/Y)-\log(X/Y)sun$

  ex. $[Fe/H]=-2.0$ → 1/100 of the solar Fe/H ratio

- Metallicity： total abundance of heavy elements (elements heavier than boron)

  important for stellar structure and evolution

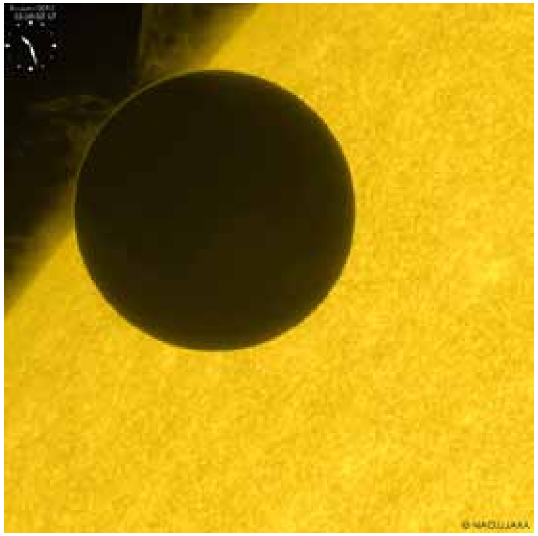
  sometimes presented as mass ratio

  ex. Solar metallicity = 0.02 (2%) or slightly lower

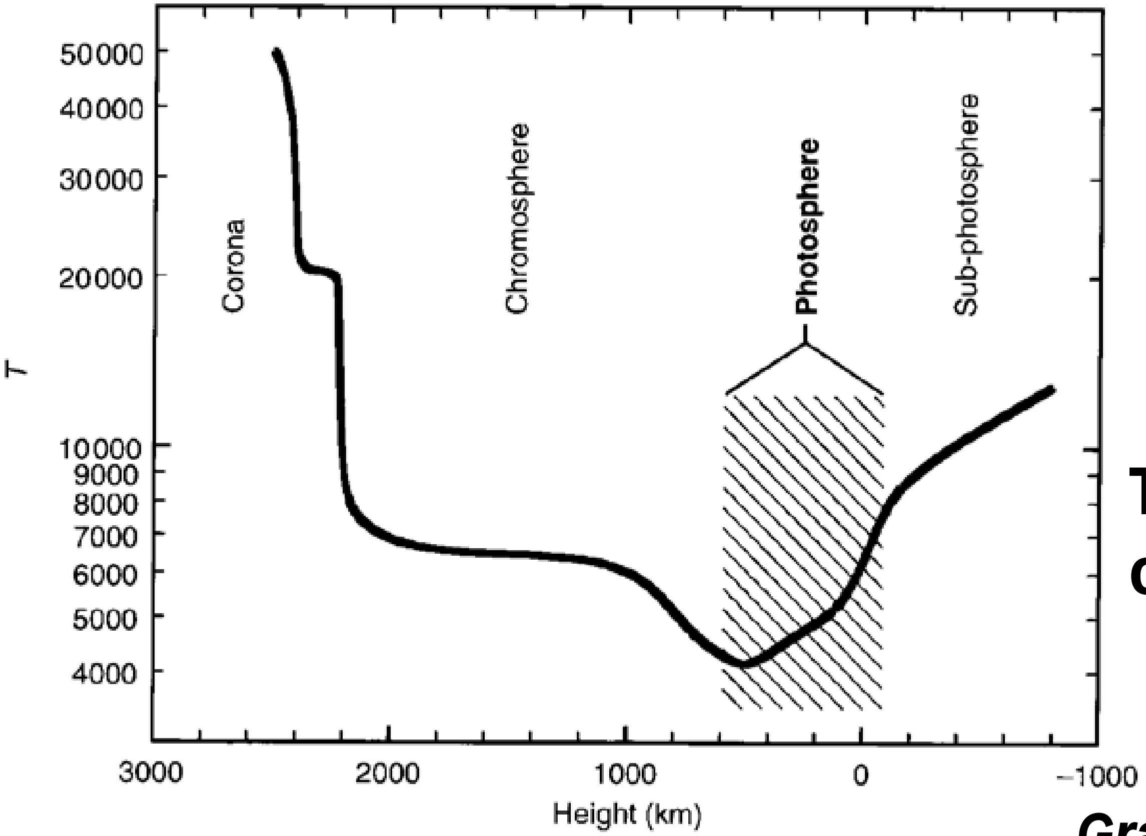
  usually represented by [Fe/H]

元素組成の測定
～スペクトル線と恒星大気モデル

Stellar atmosphere



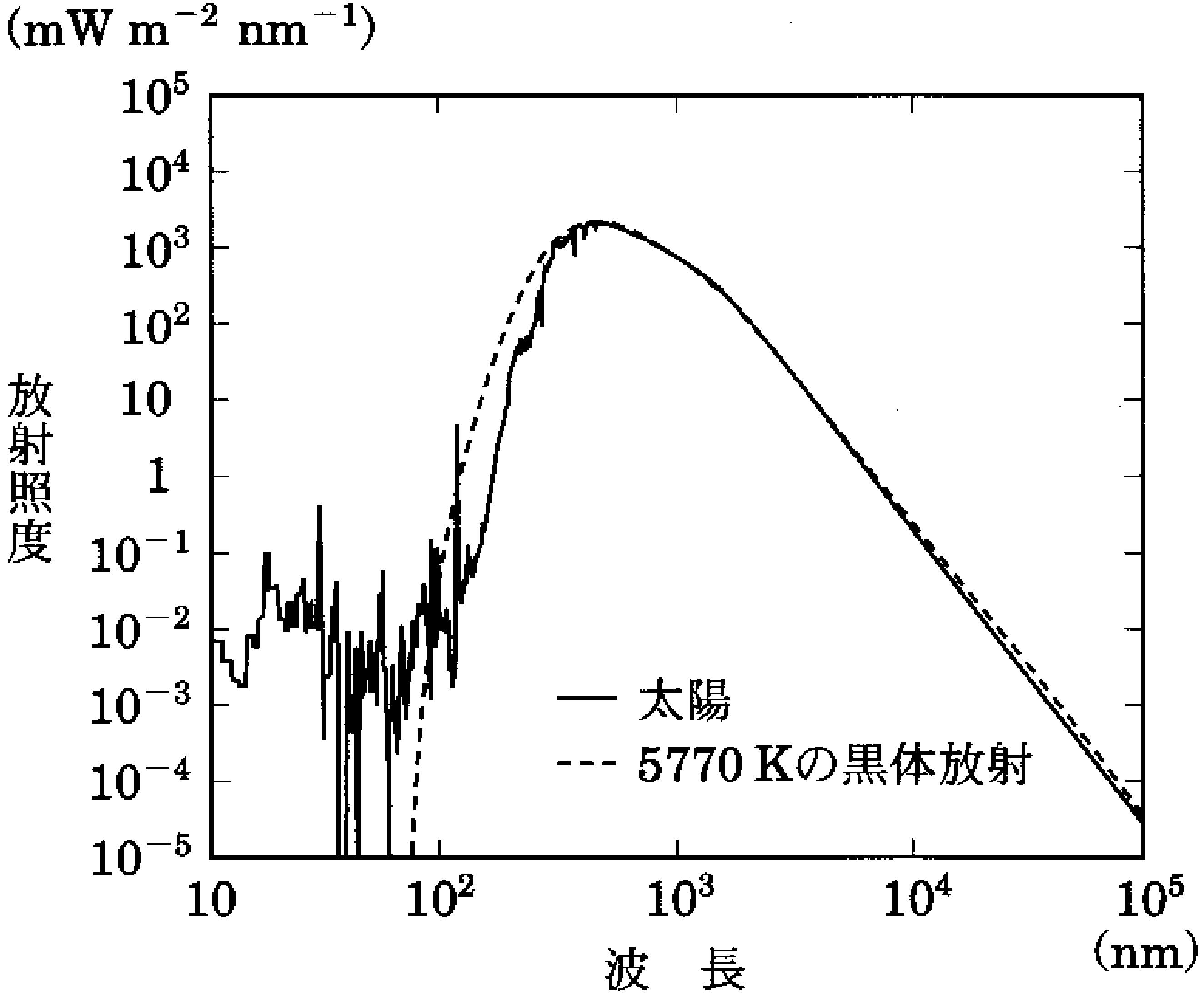
Solar atmosphere with Venus (Hinode)



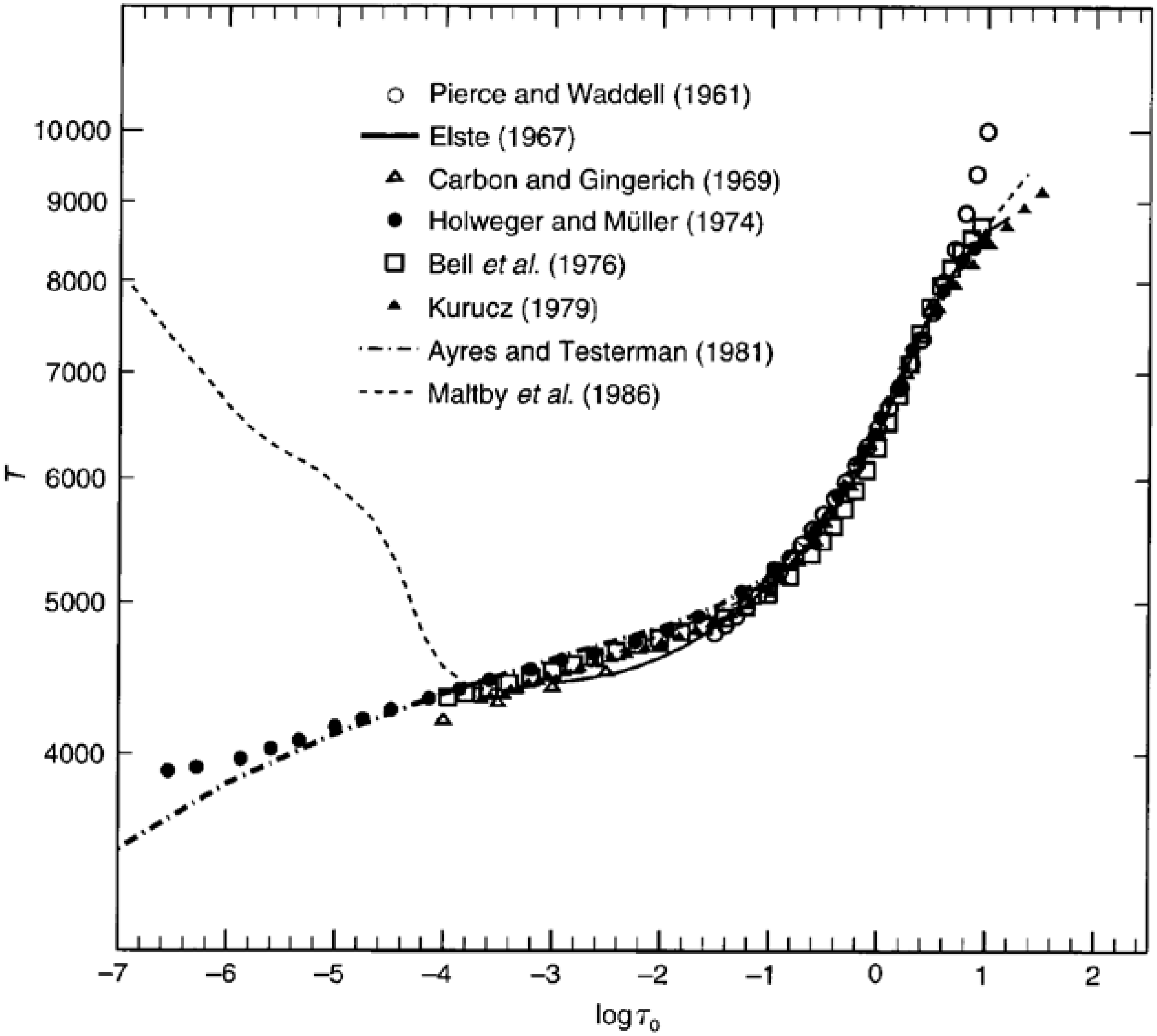
Temperature structure of the solar atmosphere

Gray 2005

Stellar atmosphere and spectra



Modeling the solar photosphere



Abundances and line strengths

「成長曲線」

curve of growth

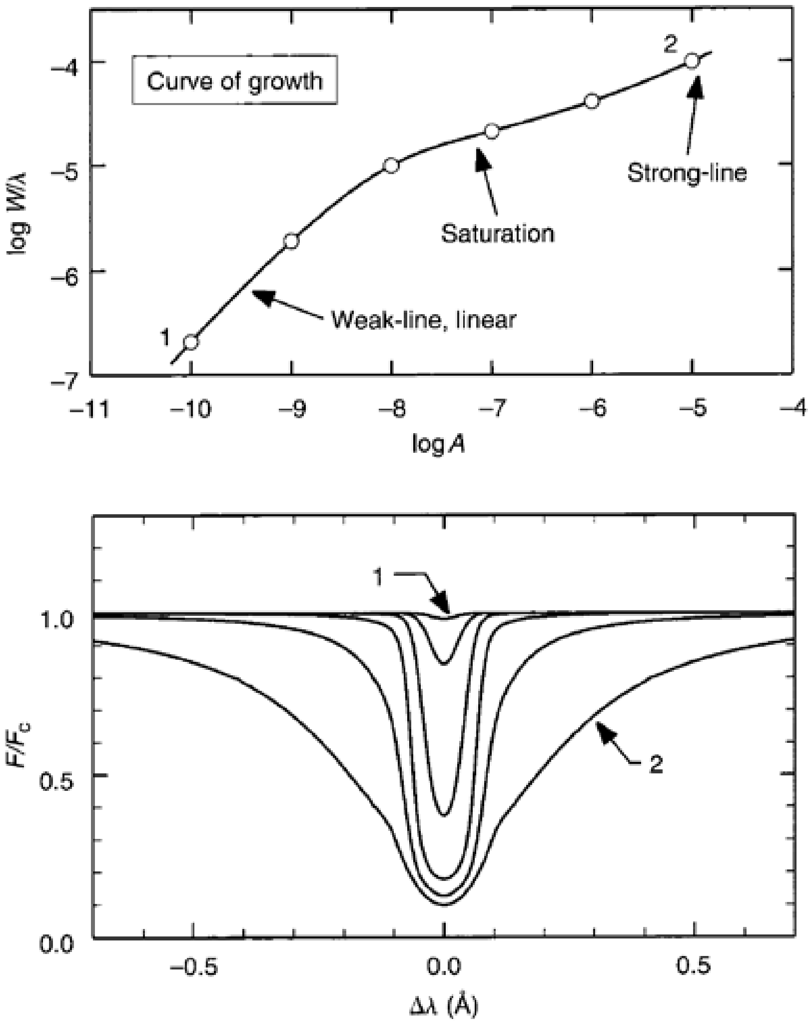


Fig. 13.11. Both the equivalent width (top) and the profile (bottom) change with chemical abundance of the absorbing species. The dots on the curve of growth correspond to the profiles below. Models have $S_0 = 0.87$ and $\log g = 4.0\,\mathrm{cm/s^2}$.

Absorption line strengths and abundance measurements

- **Measurements from weak lines**

○ line strength is in proportion to abundance

→not severely model dependent

× difficulty in line detection, sensitive to S/N of data

× sensitive to contamination of other lines

- **Measurements from strong lines**

○ easy to detect lines, measurement of line can be accurate (though Gaussian fitting is not applicable.)

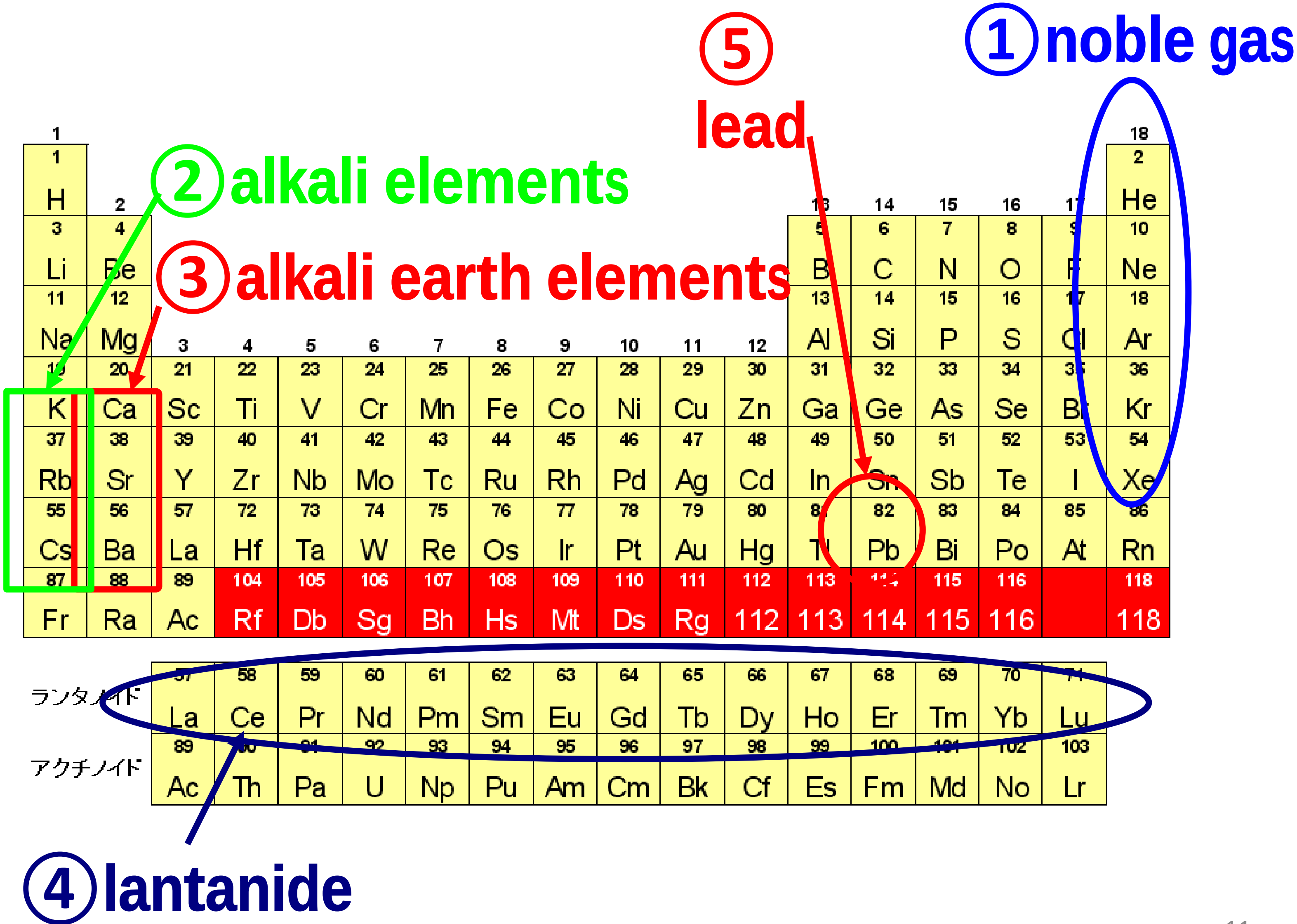
× insensitive to abundances

→low accuracy in abundance determination
dependent on treatment of line broadening

× line formation in upper photosphere, for which modeling is difficult in general

どの元素なら測れるか
何が信頼できるか

Which elements can be measured?



⑤ **lead**

① **noble gas**

② **alkali elements**

③ **alkali earth elements**

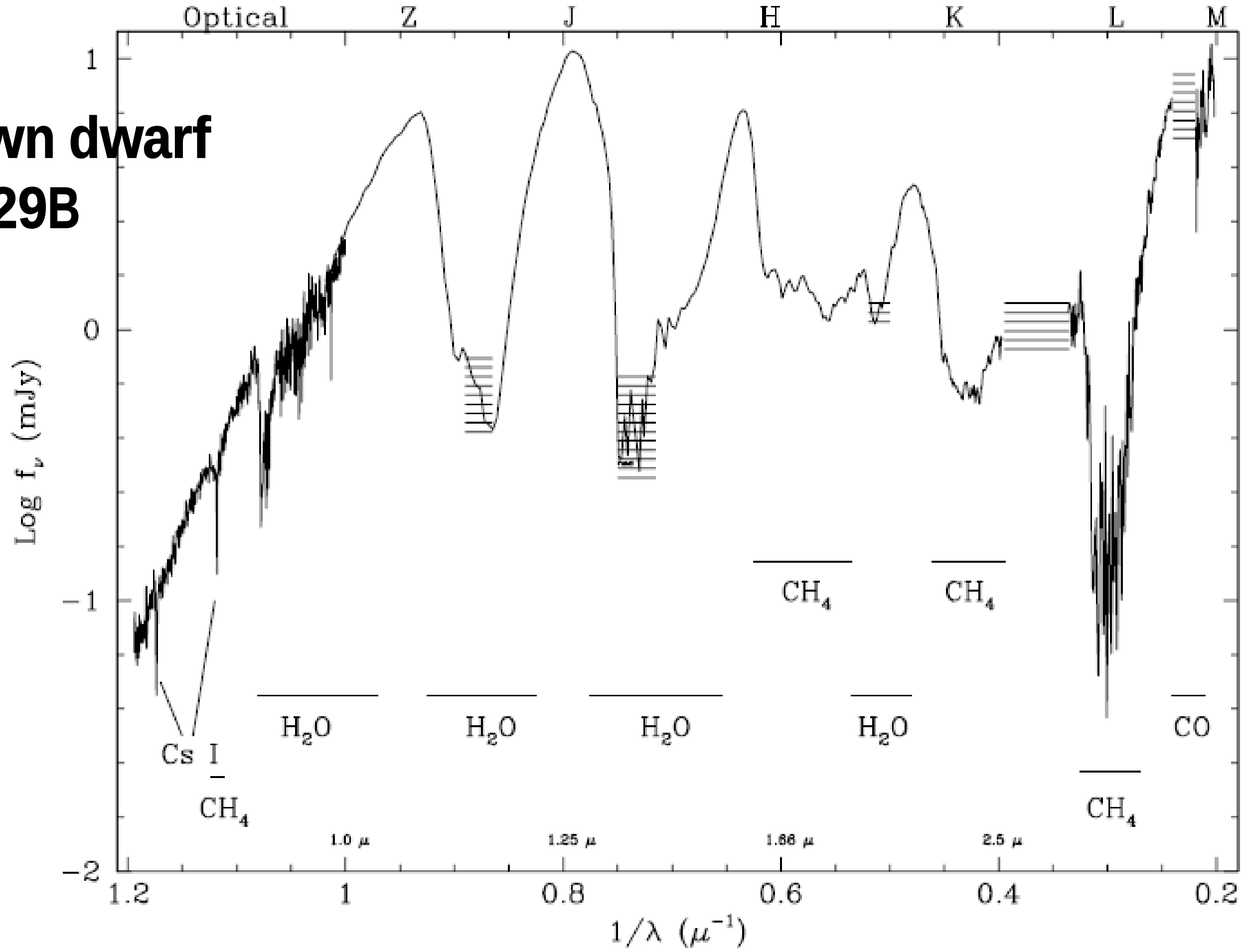
④ **lantanide**

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1 H																	2 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	18 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
55 Cs	56 Ba	57 La	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
87 Fr	88 Ra	89 Ac	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 112	113 113	114 114	115 115	116 116		118 118

ランタノイド	57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
アクチノイド	89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr

Cs absorption lines in brown dwarfs

Brown dwarf GL229B



Oppenheimer et al. (1998)

Which elements can be measured?

①noble gas:Ar, Kr,...

No useful spectral features in the optical range measurable for cool stars. Emission lines are detectable in planetary nebulae.

②alkali elements: Na, K, Rb, Cs

Mostly ionized in stellar atmosphere. Remaining Na and K have however strong doublet features. Rb and Cs are detectable only in very cool stars.

③alkali earth elements: Mg, Ca, Sr, Ba

Singly ionized species have strong doublet lines (ex. Ca K lines) and easily detectable even in metal-poor stars.

④lantanide:La, Ce, Pr, Nd, Sm, Eu, Gd, Dy, ...

Many lines of singly ionized stage exist in the optical. Relative abundances are well determined.

⑤lead

Measurable lines exist in the optical range.

Stellar chemical composition 〜what can we believe?

- “absolute values” of abundances (abundance ratio with respect to H) are uncertain due to many error sources

  e.g. controversy on the solar Fe abundance (log(Fe/H)〜-4.50) in the past 20 years

- Abundances determined from the species that dominate in isonization stages are reliable.

  e.g. Fe abundances from Fe II lines in the Solar spectrum

- Abundance ratios are robust in general.
  e.g. Eu/Fe, La/Eu

- “relative abundance” between two similar type stars are reliable (in particular the results of differential analyses)

Error sources in abundance analyses

- Noise in observed spectrum (S/N), error in measurement of equivalent widths (→ random error)

  →estimate from S/N, fitting error etc.
- Error in transition probability (random error?)

- Incompleteness of model photosphere (→systematic?)
- Incompleteness of spectrum calculation (NLTE effects etc.) (→ systematic for each line, but depends on lines used)
- Uncertainty of stellar parameters

  estimates from spectral analysis →random + systematic

  independent estimates (e.g. color index)

  → random + systematic

- Uncertainty in solar abundances used to derive abundance ratios ([X/Fe])

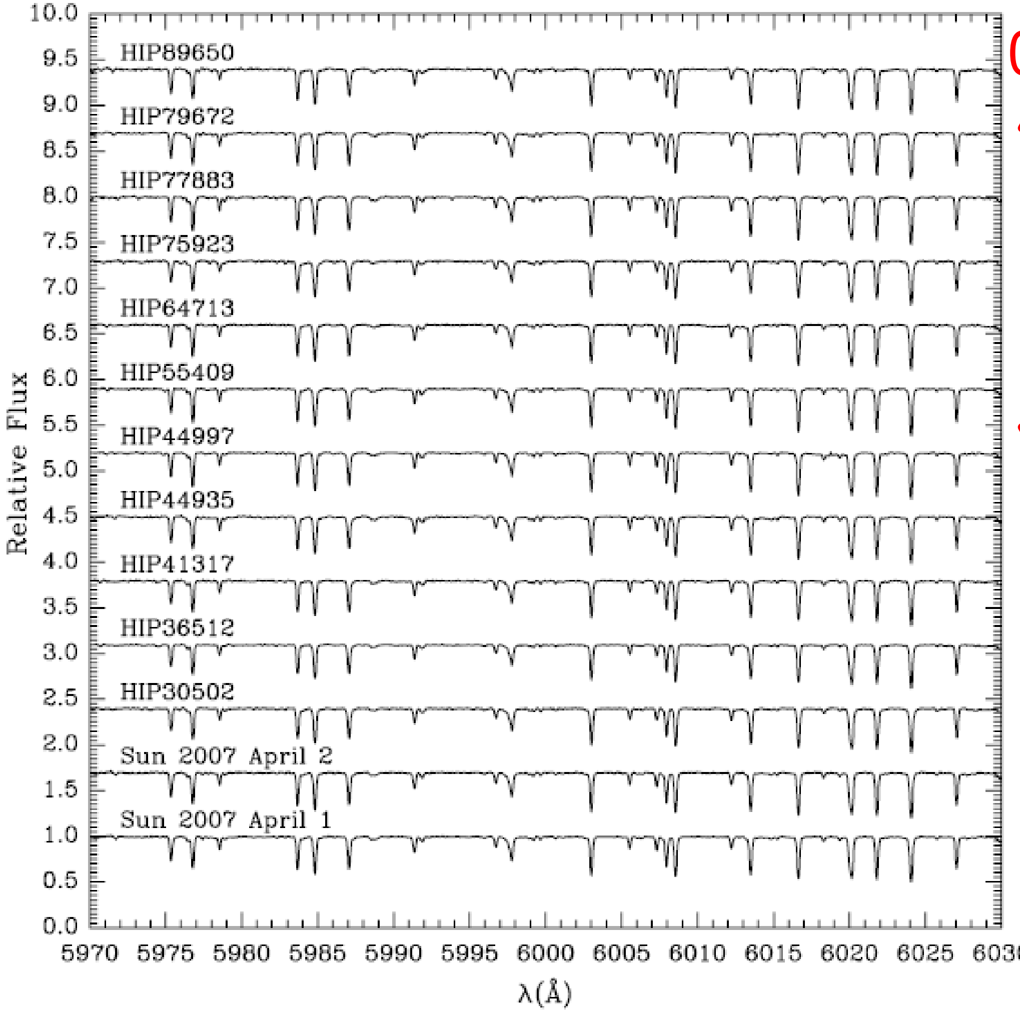
Avoiding errors by differential analysis

Differential analysis: deriving abundance ratio with respect to a standard star (ex. the Sun)

- **Noise in observed spectrum (S/N)、error in measurements of equivalent widths**
  (→unavoidable)
- **Error in transition probability**
  →avoidable by using the same line
- **Incompleteness of model photospheres**
  →(mostly) avoidable for the same type of stars
- **Incompleteness of spectrum calculations**
  →(mostly) avoidable by using the same line for the same type of stars
- **Uncertainty of stellar parameters**
  →avoidable for the systematic components

Differential analysis for “solar twin” stars

Melendez et al. (2009)



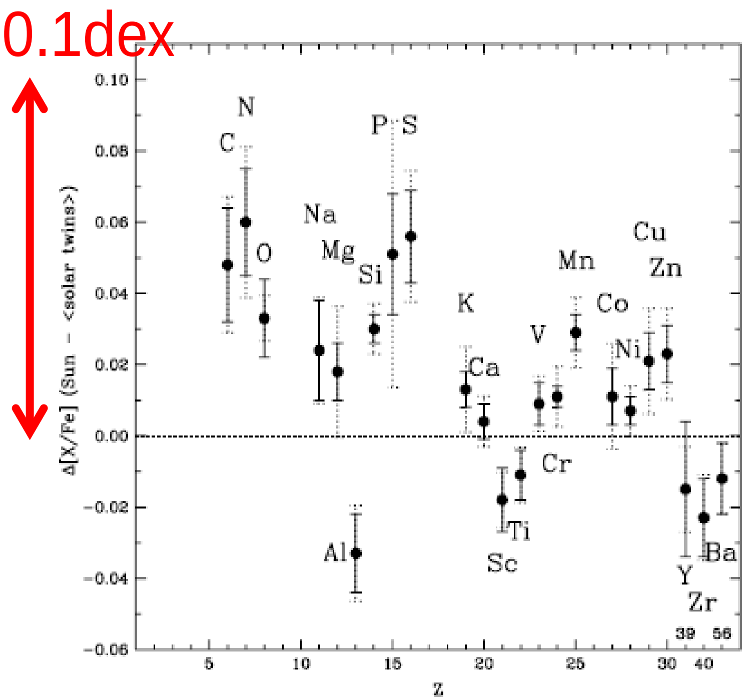


Figure 2. Differences between [X/Fe] of the Sun and the mean values in the solar twins as a function of atomic number Z. For clarity, the elements Y ($Z = 39$), Zr ($Z = 40$), and Ba ($Z = 56$) have been included after Zn. Observational 1σ errors in the relative abundances (including observational errors in both the Sun and solar twins) are shown with dotted error bars, while the 1σ errors in the mean abundance of the solar twins are shown with solid error bars.

太陽系組成

Solar abundances

- **Determination of abundances by spectral line analysis (as for stars)**
  - **almost all elements including volatile elements C, N, O, ...**
  - **advantage of solar spectral analysis**
    - **very high quality spectrum**
    - **accurate model parameters**
    - **spatially resolved spectra**
- **Determination of abundances from meteorites analysis**
  - **metal abundances**
  - **advantages**
    - **very accurate**
    - **isotope ratios**
- **Solar wind, corona etc.**
    - **noble gases He, Ne, Ar, ...**

Analysis and compilation of solar abundances

- Anders & Grevesse (1989)
  - analysis based on 1D model atmosphere
  - meteorite analysis

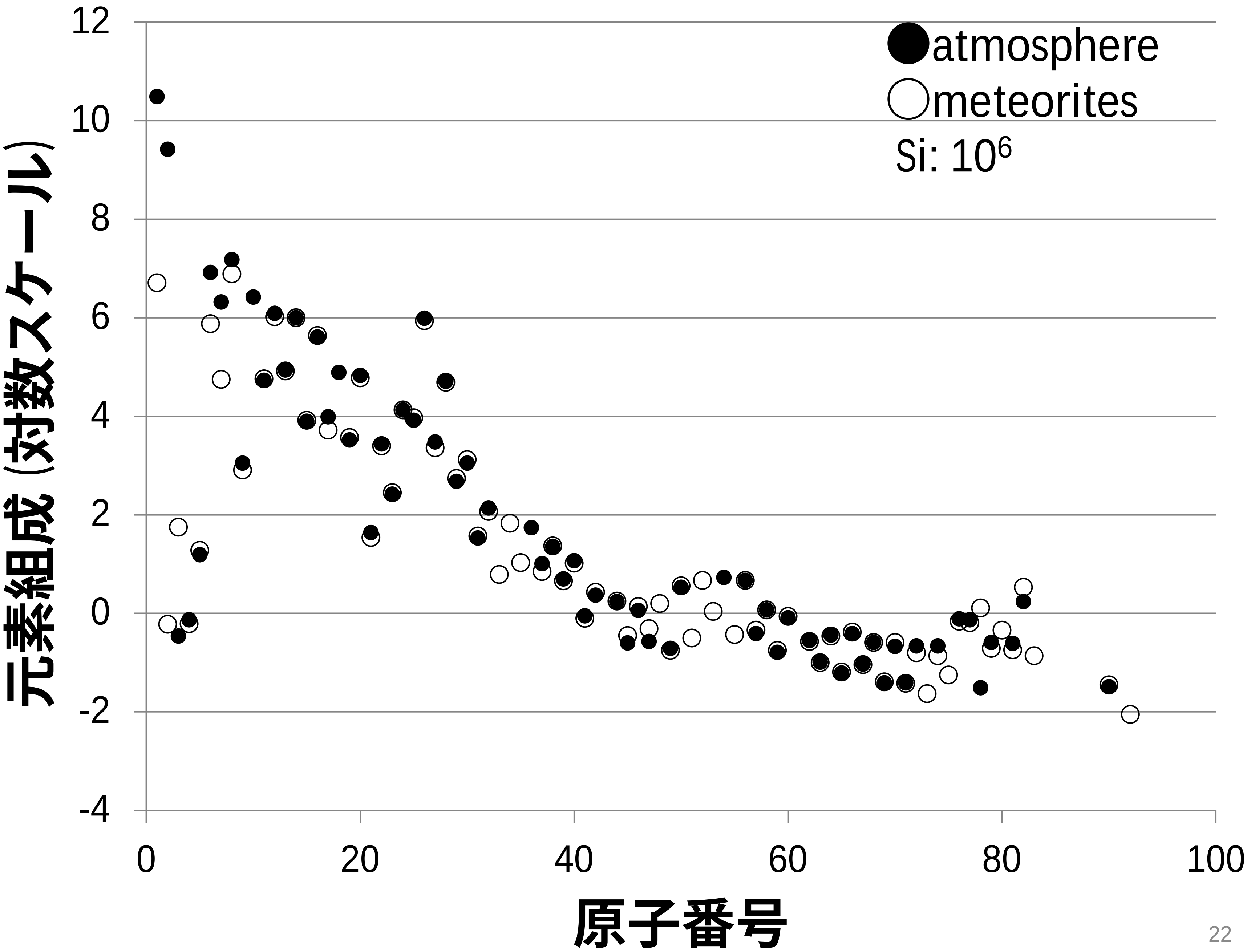
- Asplund et al. (2009)
  - analysis based on 3D model atmosphere
  - updated atomic data
  - meteorite analysis

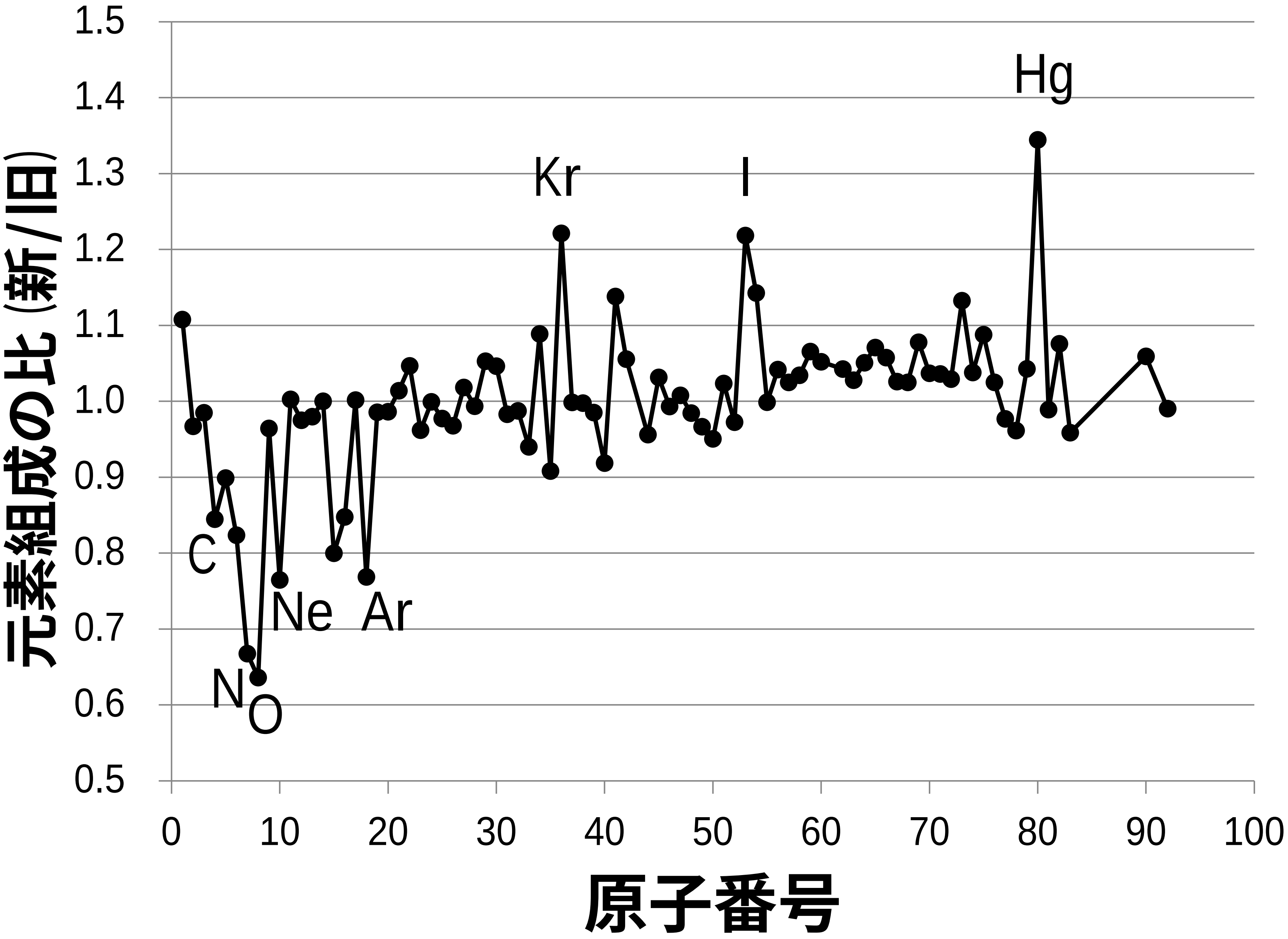
Cf. 理科年表「宇宙の元素組成」

Recent measurements of transition probability for rare earth elements

Experiments have been conducted from astronomical interests

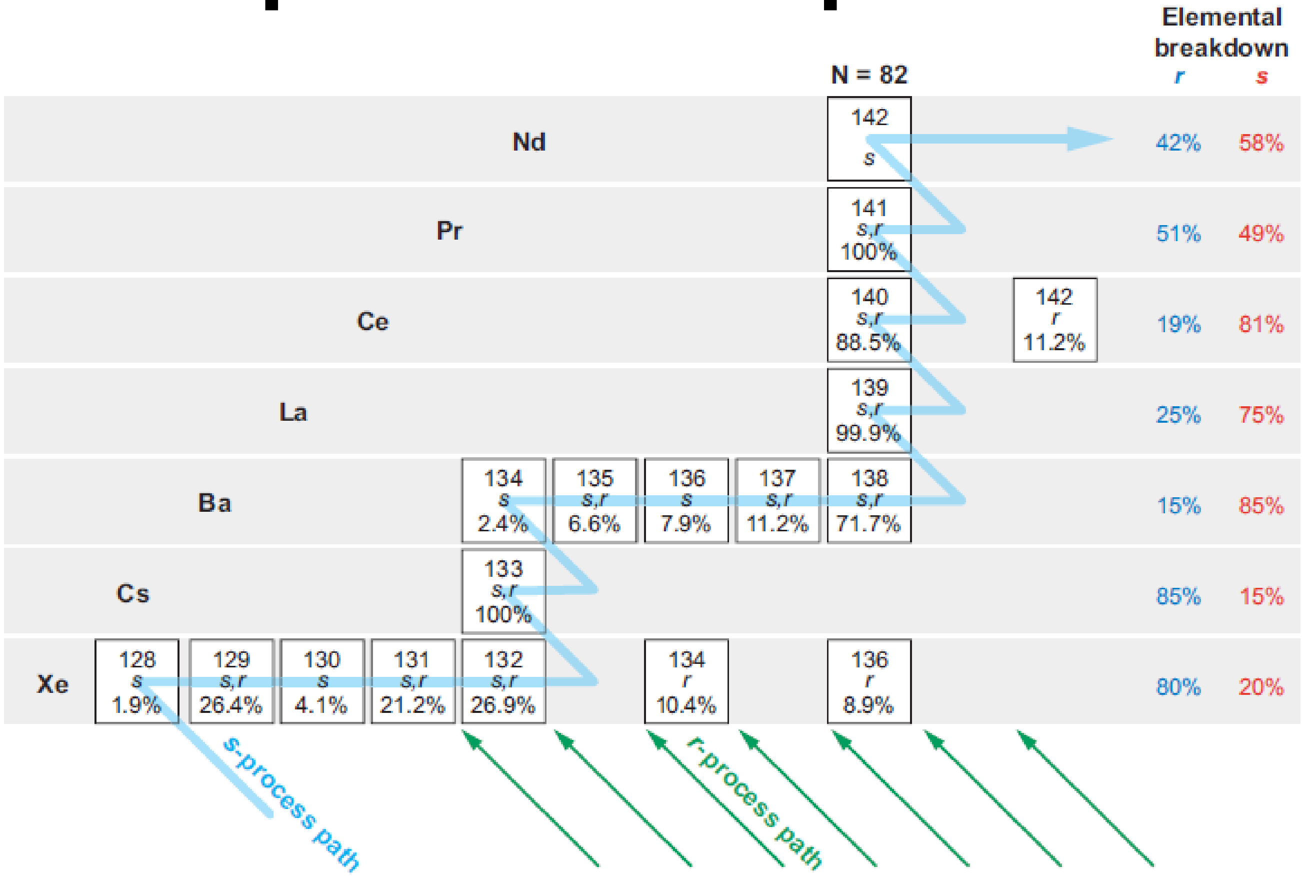
La II: Lawler et al. (2000, ApJ, 556, 452)
Eu II: Lawler et al. (2001, ApJ, 563, 1075)
Tb II: Lawler et al. (2000, ApJS, 137, 341)
Nd II: Den Hartog et al. (2003, ApJS, 148, 543)
Ho II: Lawler et al. (2004, ApJ, 604, 850)
Pt I: Den Hartog et al. (2005, ApJ, 619, 639)
Sm II: Lawler et al. (2006, ApJS, 162, 227)
Gd II: Den Hartog et al. (2006, ApJS, 167, 292)
Hf II: Lawler et al. (2007, ApJS, 169, 120)
Er II: Lawler et al. (2008, ApJS, 178, 71)
Ce II: Lawler et al. (2009, ApJS, in press)
Pr II, Dy II, Tm II, Yb II, Lu II: Sneden et al. (2009, ApJS)
....


● atmosphere
○ meteorites
Si: 10^6
元素組成（対数スケール）
原子番号
12
10
8
6
4
2
0
-2
-4
0
20
40
60
80
100


元素組成の比 (新/旧)
1.5
1.4
1.3
1.2
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0
10
20
30
40
50
60
70
80
90
100
原子番号
Hg
Kr
I
C
Ne
Ar
N
O

太陽系組成の
sプロセス・rプロセス成分

Neutron-capture processes: s-process and r-process

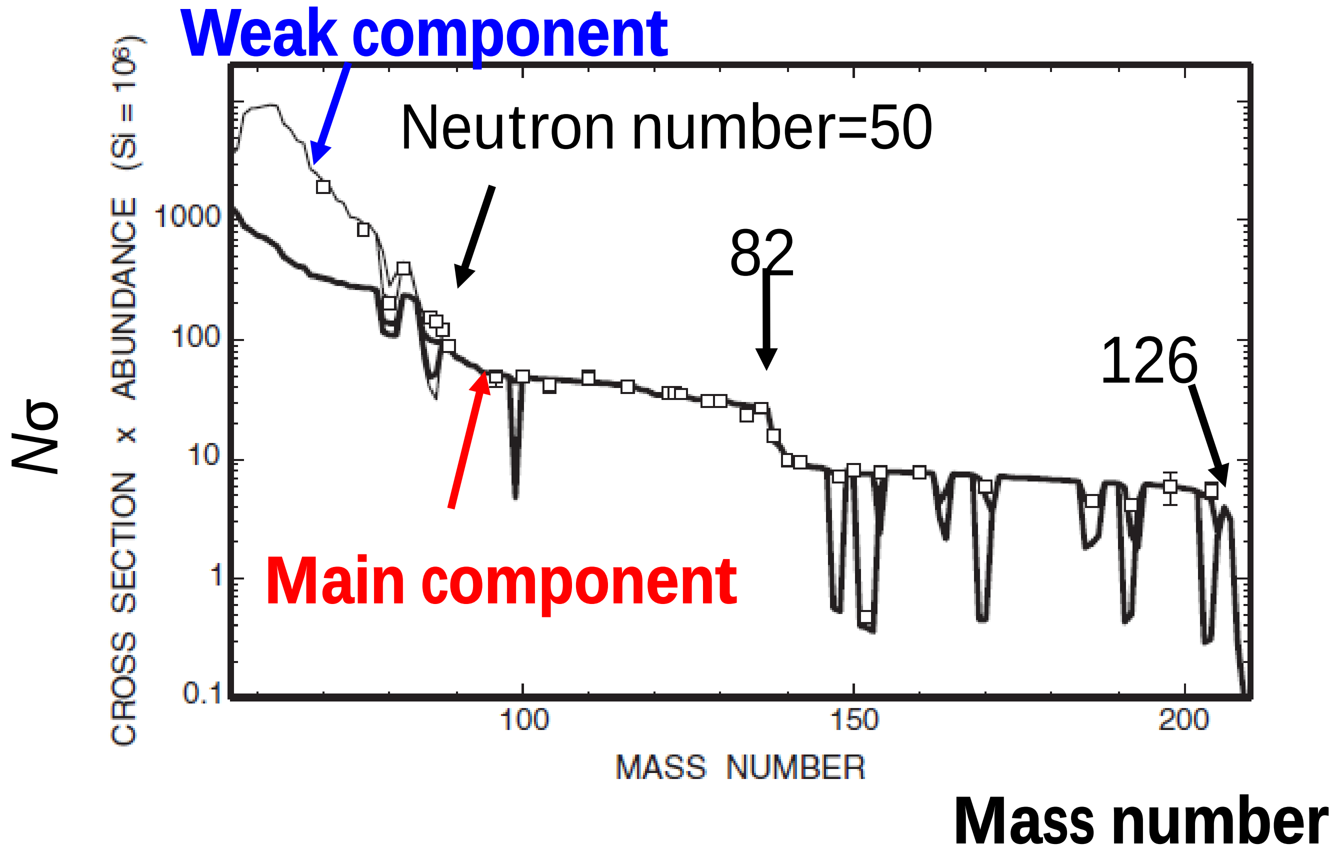


Sneden et al. (2008)

s-process classical model

Steady flow neutron-capture → *N*σ～constant

(σ: neutron-capture cross section)



Weak component

Neutron number=50

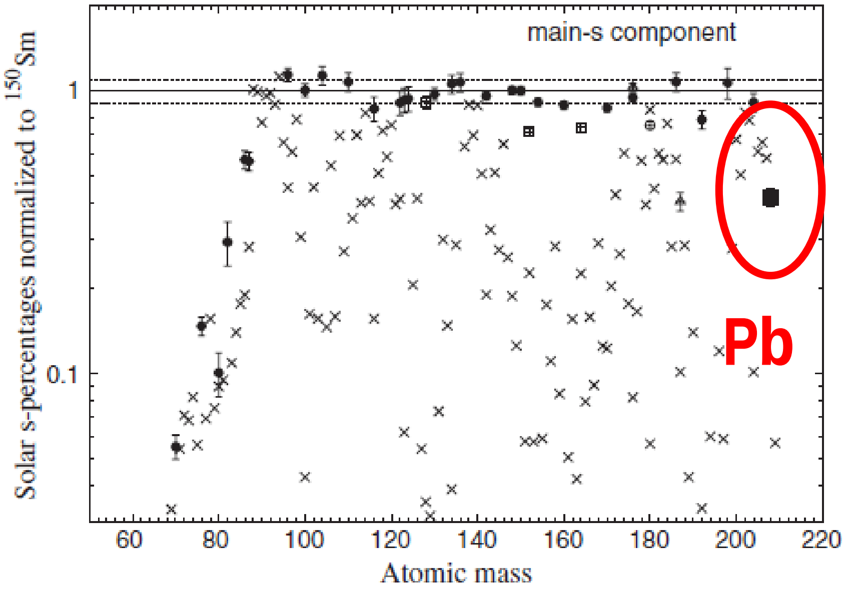
82

126

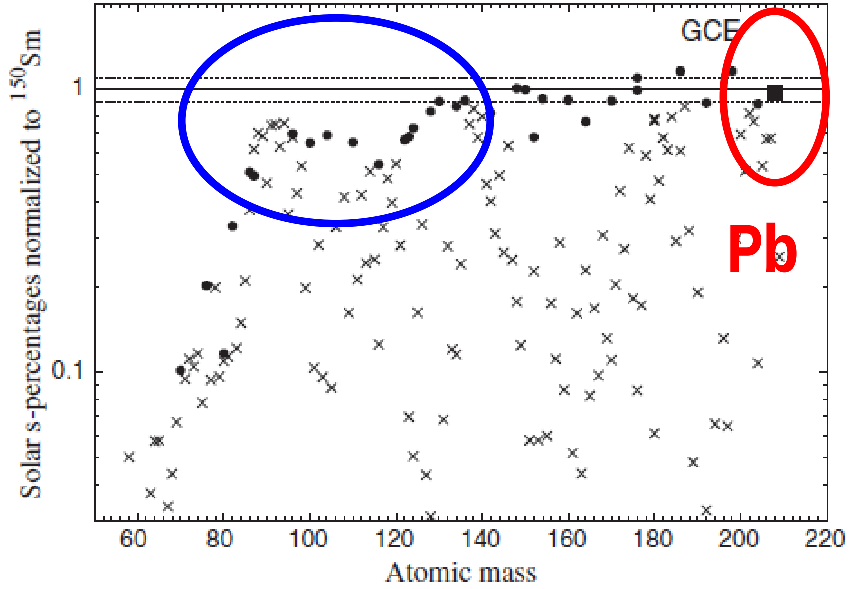
Main component

s-process model compared to solar s-process component

s-process model for a single object



s-process models + chemical evolution model including metallicity effects



Käppeler, Gallino, Bisterzo, Aoki (2011, Rev. Mod. Phys.)

r-process: explosive synthesis of heavy elements

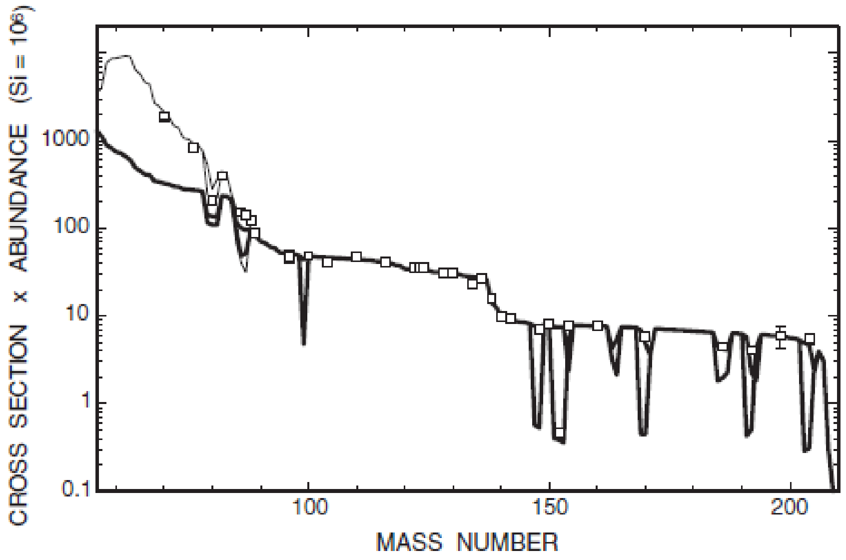
- **r-process: neutron-capture with very short times-cale (<< 1 sec)**
→process through unstable nuclei

- **Site/phenomena responsible for r-process are still unknown: candidates are core-collapse supernovae and related objects, and merger of neutron stars**

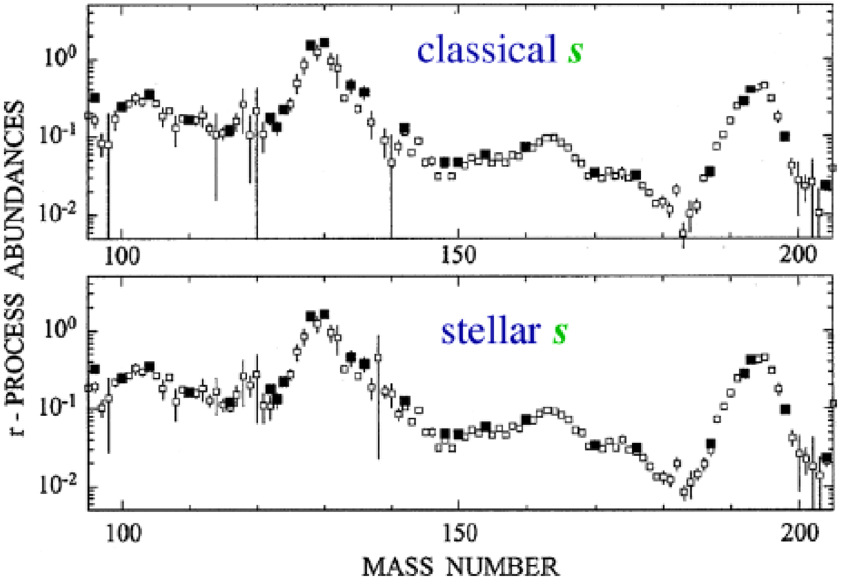
- **Abundance pattern of the r-process component in solar-system material is the "residual" of solar abundance from which the s-process component is subtracted.**

Analysis of solar abundance: s-process v.s. r-process

Estimate of the s-process component



Residual = the r-process component

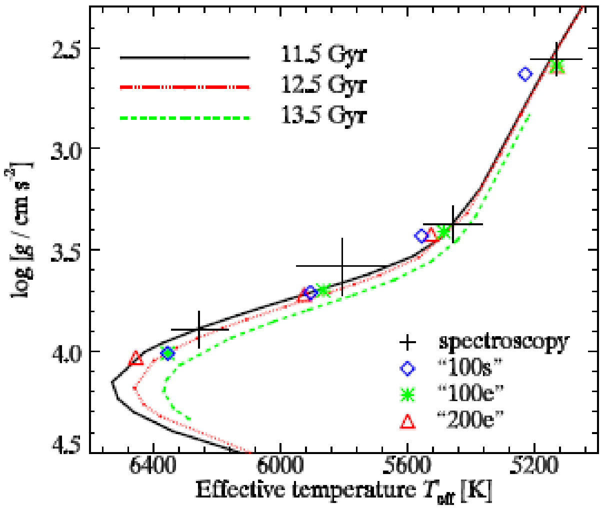


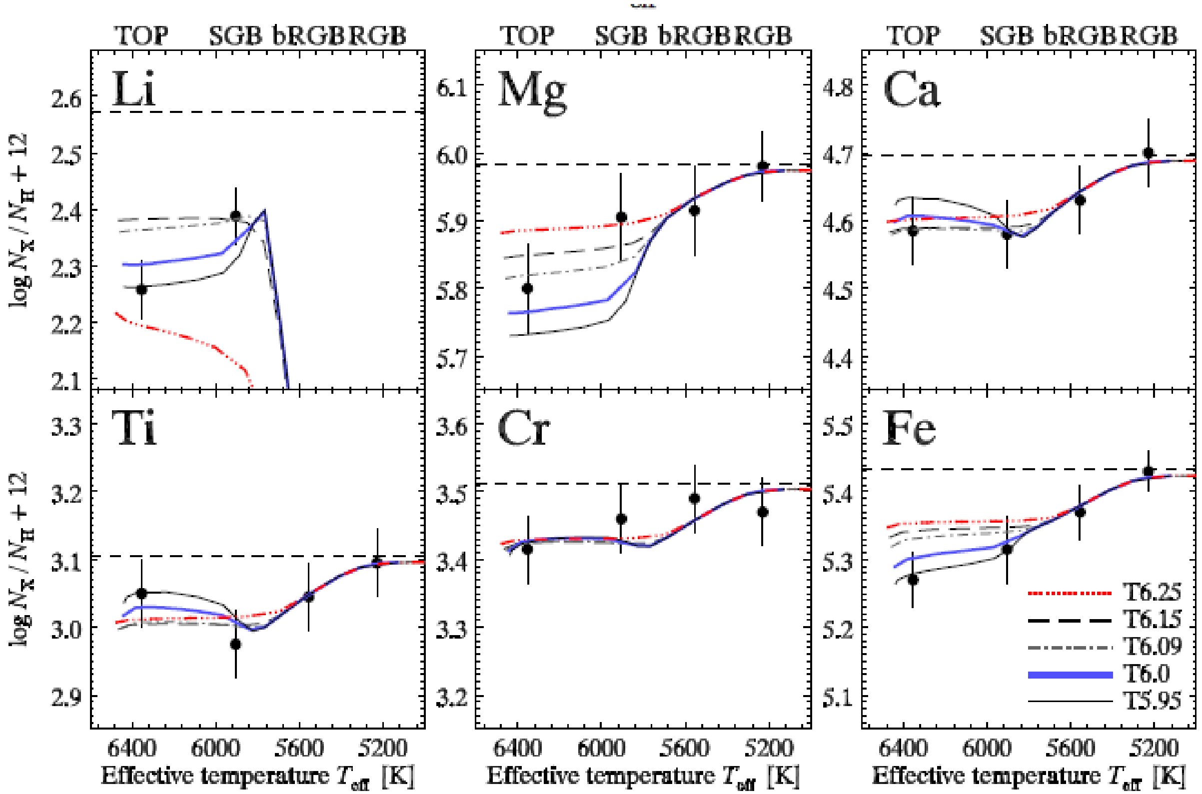
Käppeler, Gallino, Bisterzo, Aoki (2011, Rev. Mod. Phys.)

星の表面組成は初期組成を保っているか？

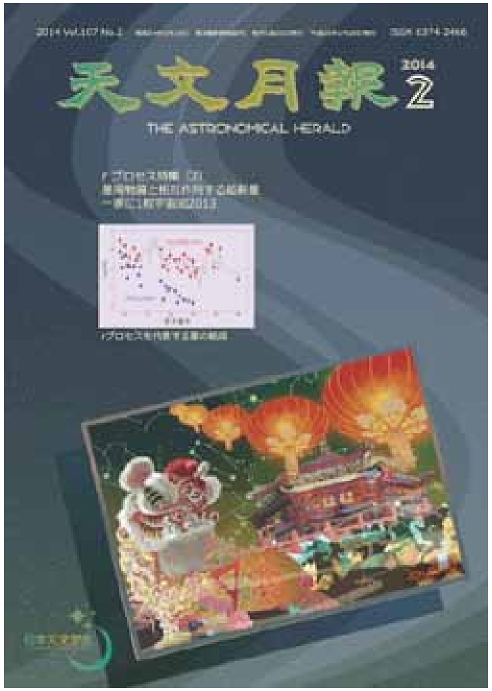
Abundances changes from main-sequence stars to red giants

Nordlander et al. (2012)





金属欠乏星の観測からのrプロセスへの制限



天文月報 2014 2

THE ASTRONOMICAL HERALD

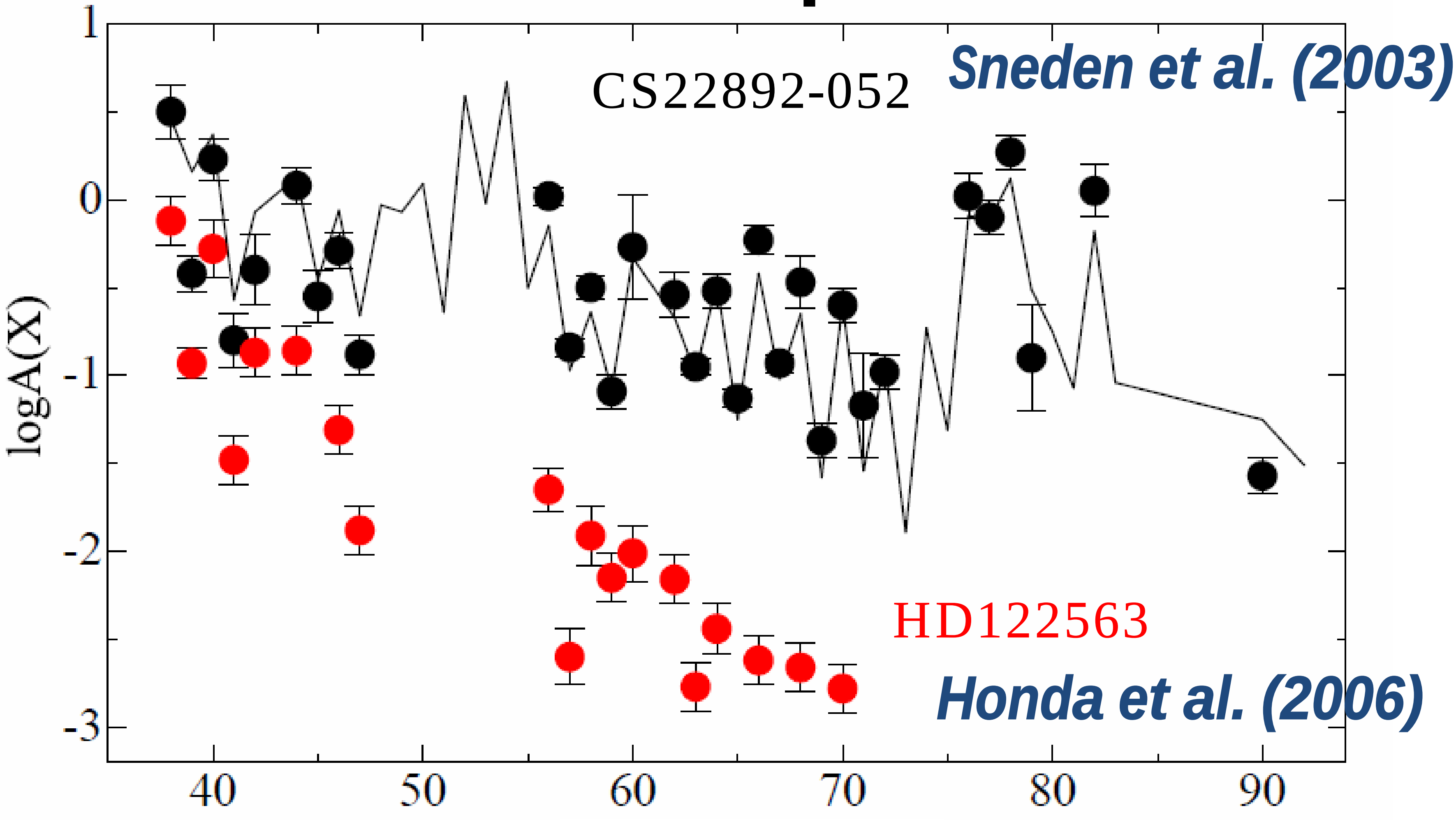
天文月報2014年1、2月号
「rプロセス特集」

青木「天文観測でrプロセスの何がわかるか」

天文月報　原稿募集中！

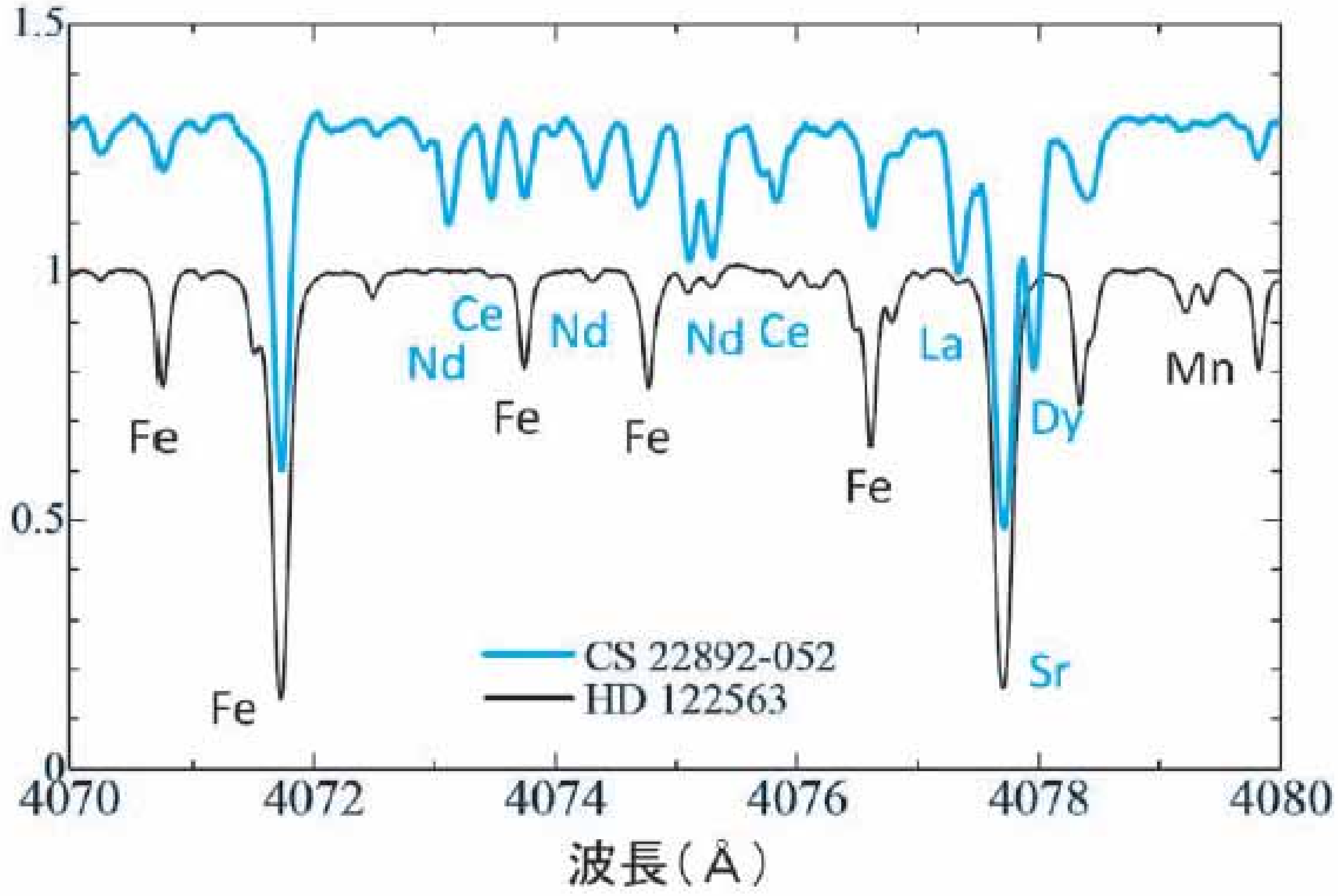
個々の金属欠乏星の
組成パターン

“main” and “weak” r-process abundance pattern

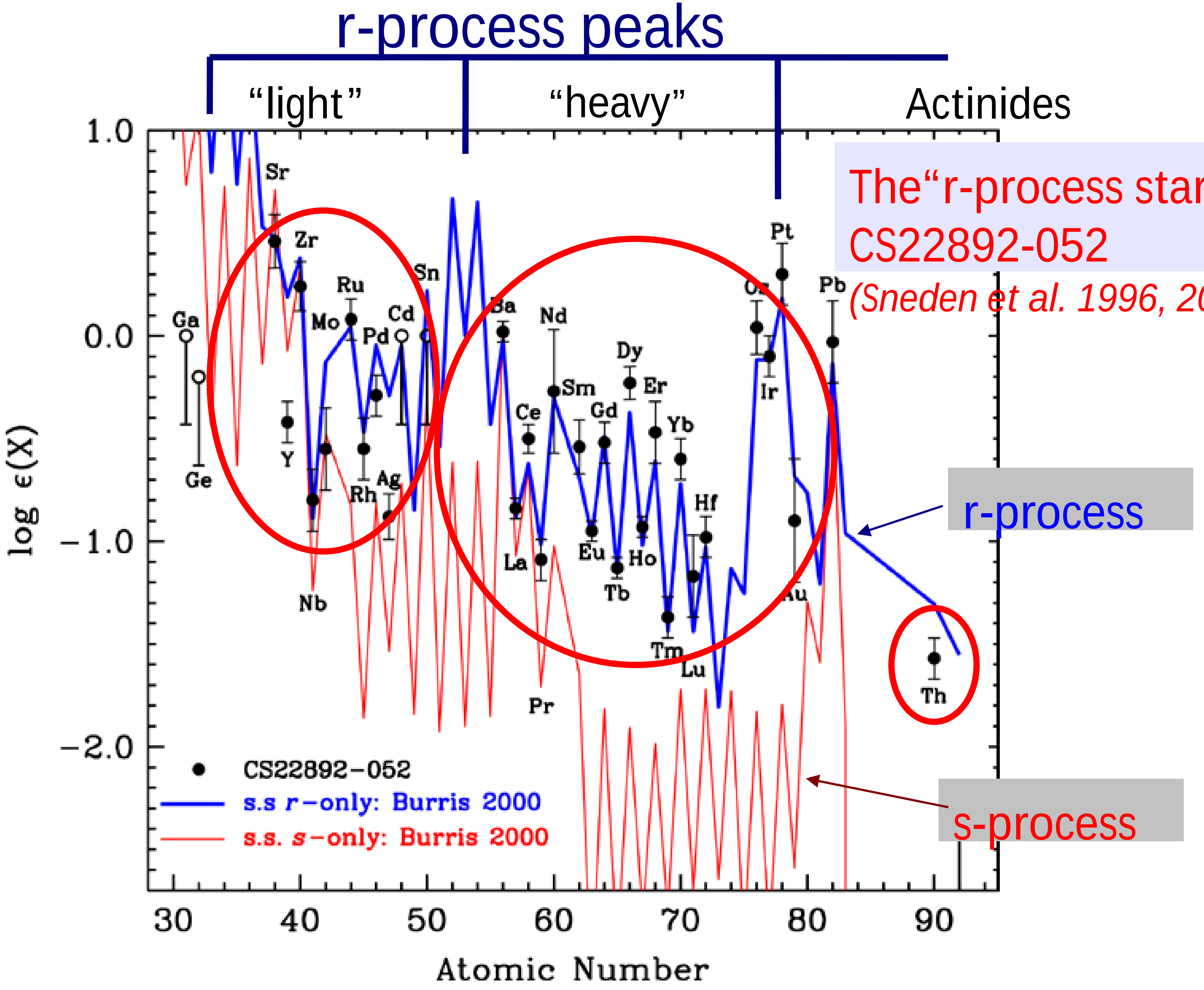


Atomic number

Spectral features of “Sneden star” and “Honda star”



r-process-enhanced stars



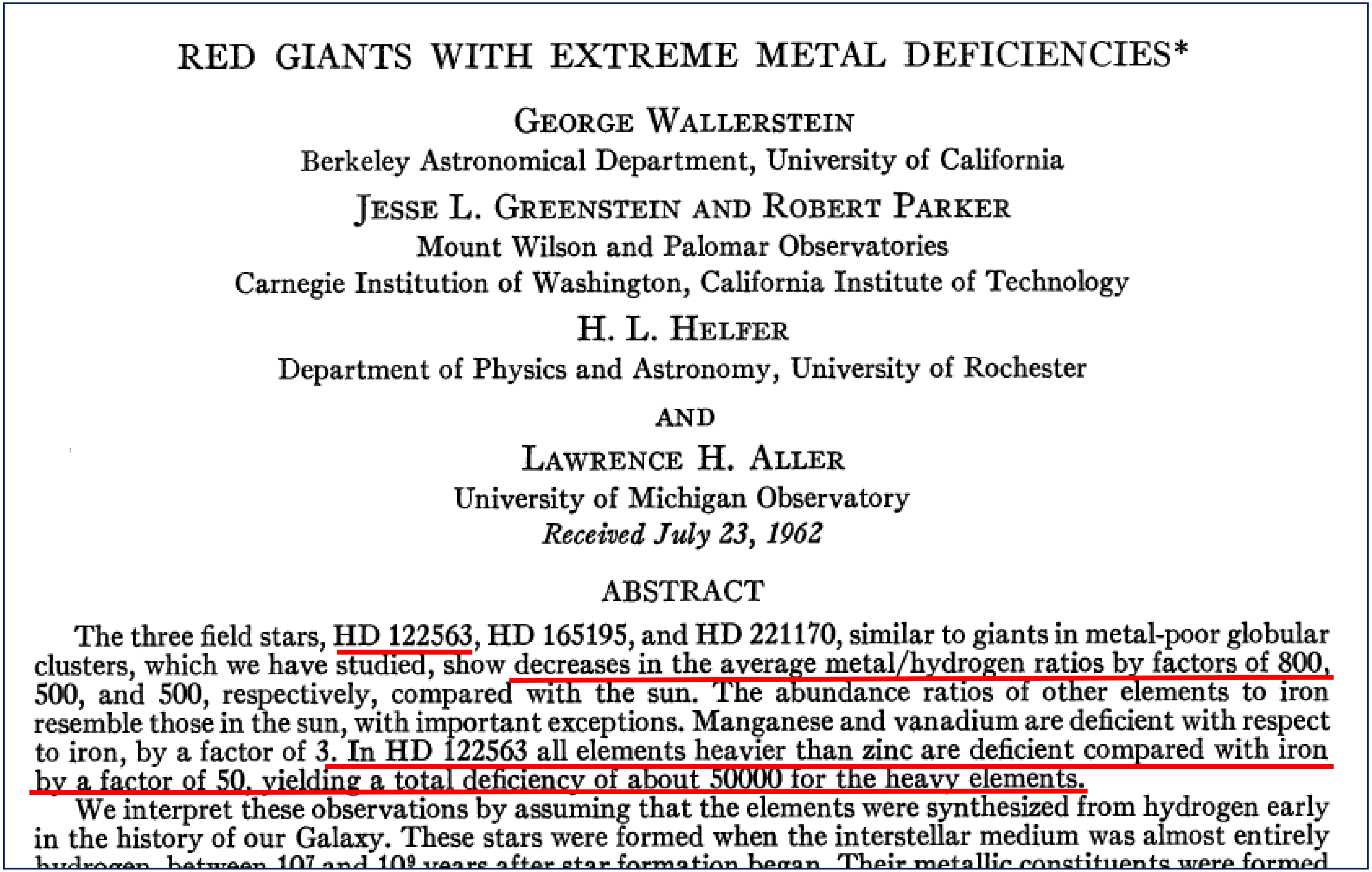
The“r-process star”
CS22892-052
(Sneden et al. 1996, 2003)

r-process

s-process

HD122563, the “Honda star”

Wallerstein et al. 1963, ApJ



RED GIANTS WITH EXTREME METAL DEFICIENCIES*

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Received July 23, 1962

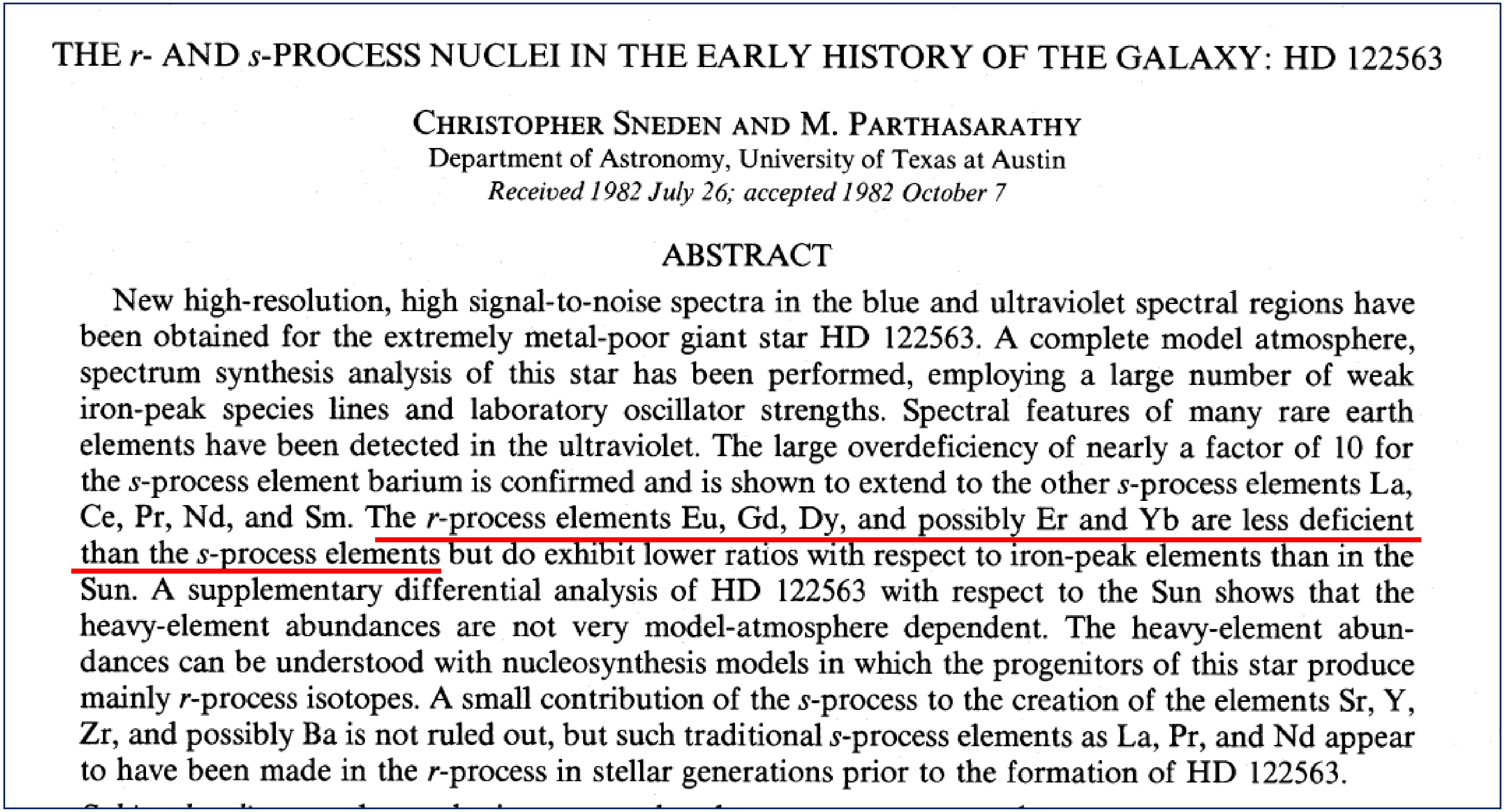
ABSTRACT

The three field stars, HD 122563, HD 165195, and HD 221170, similar to giants in metal-poor globular clusters, which we have studied, show decreases in the average metal/hydrogen ratios by factors of 800, 500, and 500, respectively, compared with the sun. The abundance ratios of other elements to iron resemble those in the sun, with important exceptions. Manganese and vanadium are deficient with respect to iron, by a factor of 3. In HD 122563 all elements heavier than zinc are deficient compared with iron by a factor of 50, yielding a total deficiency of about 50000 for the heavy elements.

We interpret these observations by assuming that the elements were synthesized from hydrogen early in the history of our Galaxy. These stars were formed when the interstellar medium was almost entirely hydrogen, between 10^7 and 10^9 years after star formation began. Their metallic constituents were formed

HD122563, the “Honda star”

Sneden & Parthasarathy 1983, ApJ



THE *r*- AND *s*-PROCESS NUCLEI IN THE EARLY HISTORY OF THE GALAXY: HD 122563

Christopher Sneden and M. Parthasarathy
Department of Astronomy, University of Texas at Austin

Received 1982 July 26; accepted 1982 October 7

ABSTRACT

New high-resolution, high signal-to-noise spectra in the blue and ultraviolet spectral regions have been obtained for the extremely metal-poor giant star HD 122563. A complete model atmosphere, spectrum synthesis analysis of this star has been performed, employing a large number of weak iron-peak species lines and laboratory oscillator strengths. Spectral features of many rare earth elements have been detected in the ultraviolet. The large overdeficiency of nearly a factor of 10 for the *s*-process element barium is confirmed and is shown to extend to the other *s*-process elements La, Ce, Pr, Nd, and Sm. The *r*-process elements Eu, Gd, Dy, and possibly Er and Yb are less deficient than the *s*-process elements but do exhibit lower ratios with respect to iron-peak elements than in the Sun. A supplementary differential analysis of HD 122563 with respect to the Sun shows that the heavy-element abundances are not very model-atmosphere dependent. The heavy-element abundances can be understood with nucleosynthesis models in which the progenitors of this star produce mainly *r*-process isotopes. A small contribution of the *s*-process to the creation of the elements Sr, Y, Zr, and possibly Ba is not ruled out, but such traditional *s*-process elements as La, Pr, and Nd appear to have been made in the *r*-process in stellar generations prior to the formation of HD 122563.

HD122563, the “Honda star”

Sneden & Parthasarathy 1983, ApJ

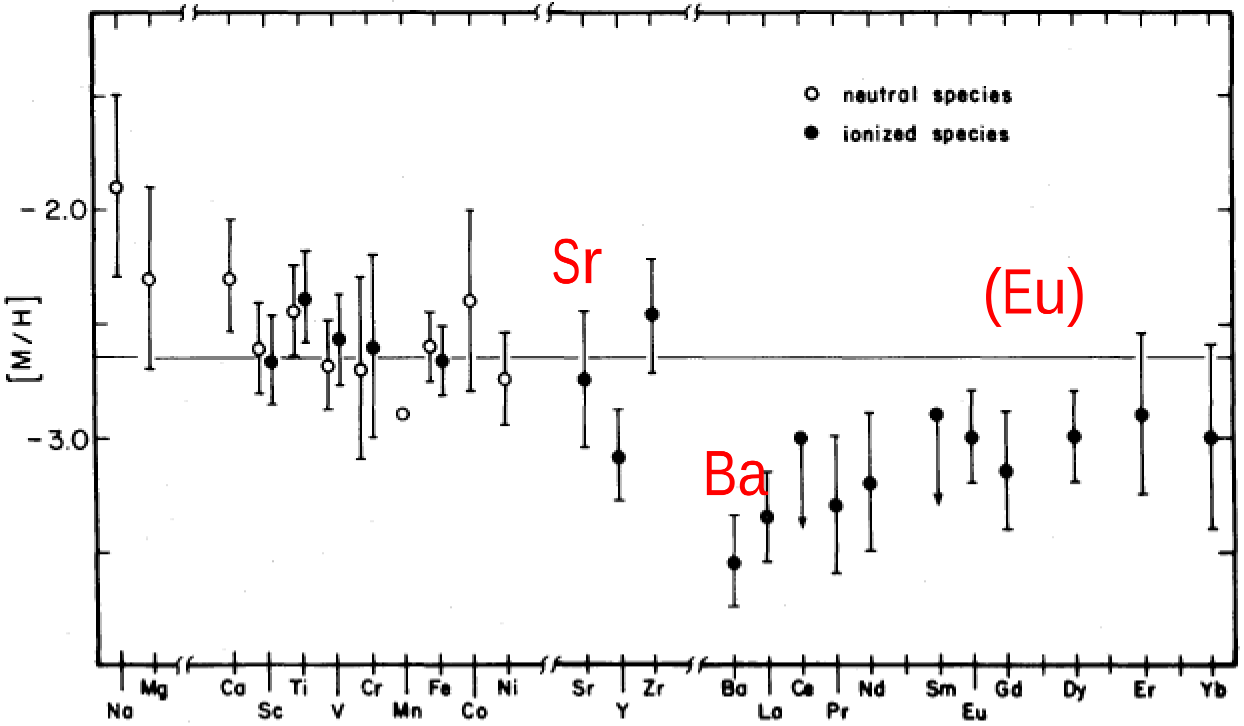
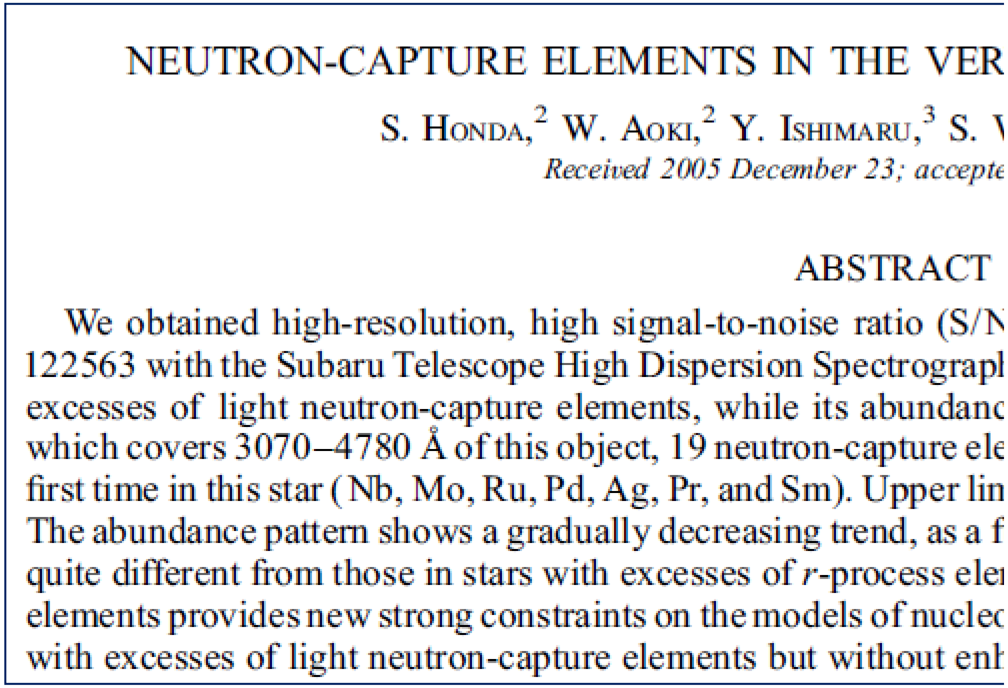


FIG. 6.—Element abundances in HD 122563. The lower temperature model was employed for these abundances.

HD122563, the “Honda star”

Honda, Aoki, Ishimaru, Wanajo, Ryan 2006, ApJ



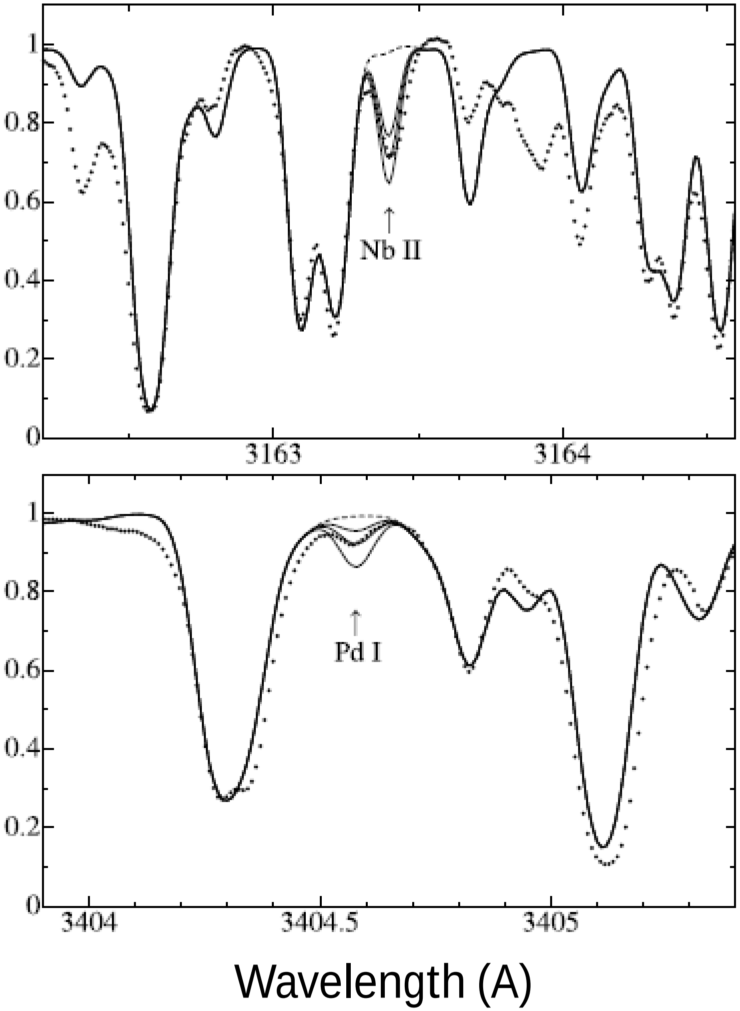
NEUTRON-CAPTURE ELEMENTS IN THE VER

S. HONDA,[2] W. AOKI,[2] Y. ISHIMARU,[3] S. V

Received 2005 December 23; accepte

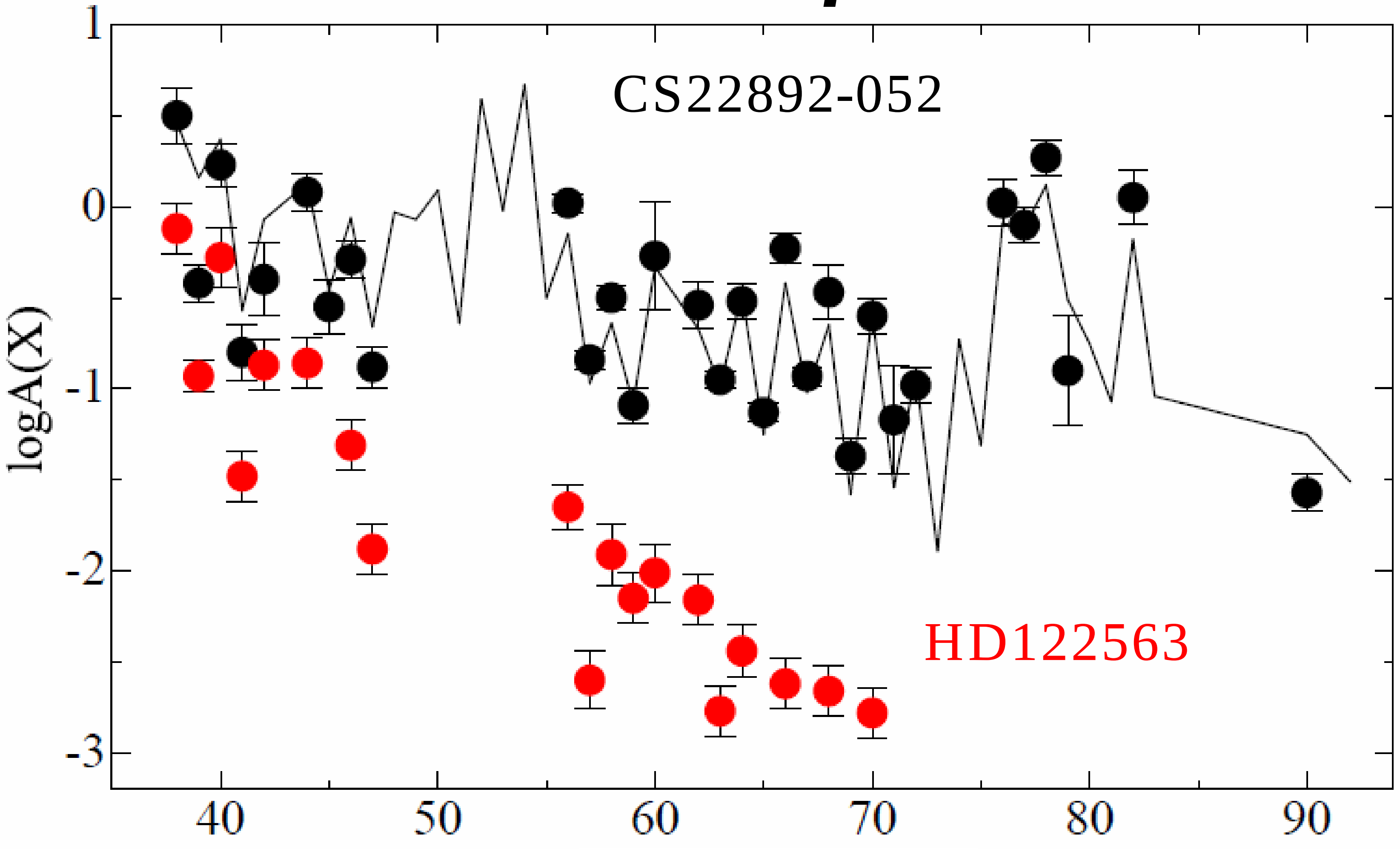
ABSTRACT

We obtained high-resolution, high signal-to-noise ratio (S/N
122563 with the Subaru Telescope High Dispersion Spectrograp
excesses of light neutron-capture elements, while its abundanc
which covers 3070–4780 Å of this object, 19 neutron-capture ele
first time in this star (Nb, Mo, Ru, Pd, Ag, Pr, and Sm). Upper lin
The abundance pattern shows a gradually decreasing trend, as a f
quite different from those in stars with excesses of *r*-process eler
elements provides new strong constraints on the models of nucle
with excesses of light neutron-capture elements but without enh



Subaru Telescope
90 minutes exposure
R=90,000
S/N~1000@4000A, 140@3100A

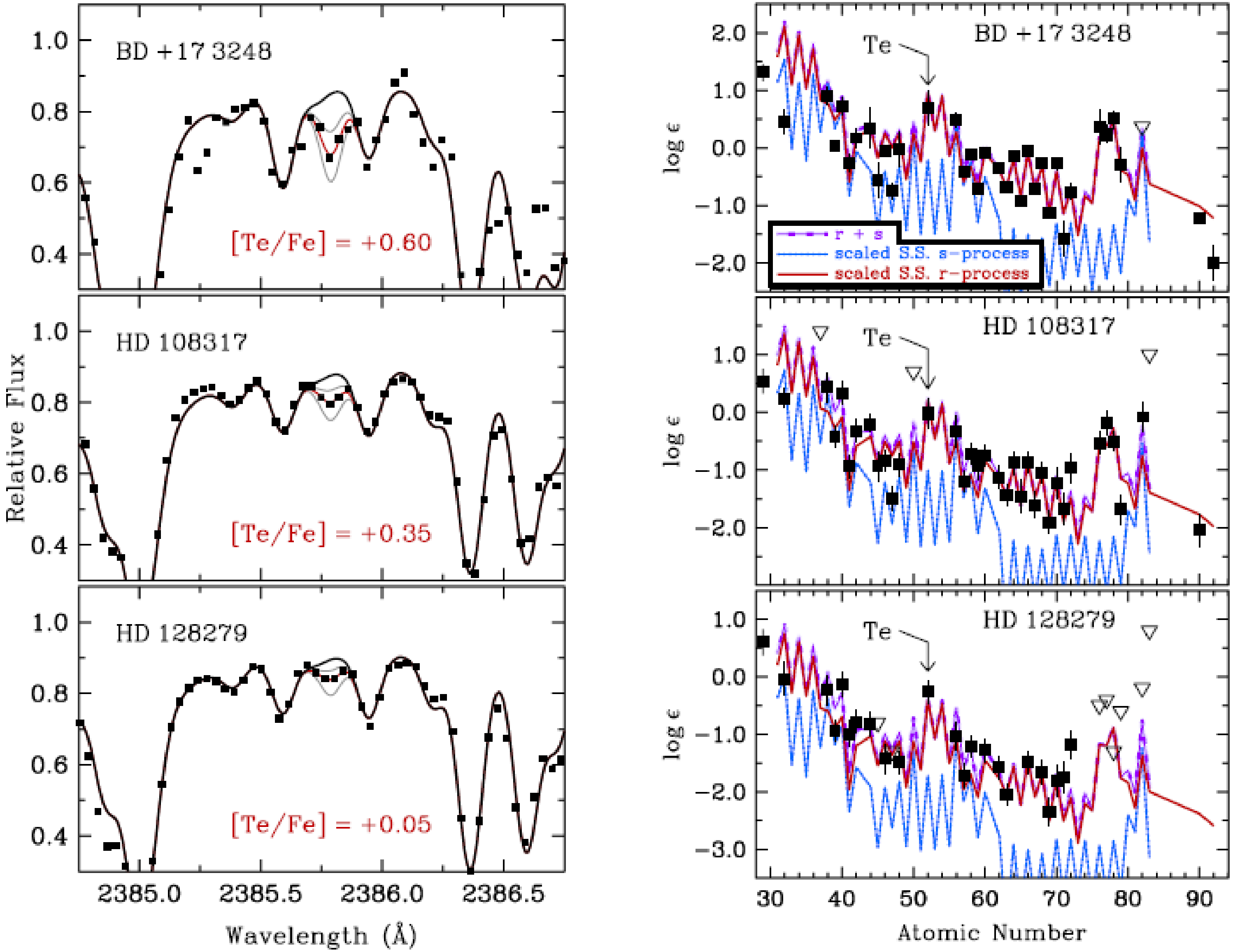
“main” and “weak” r-process abundance pattern



Atomic number

2nd peak element Te detected in HST UV spectra

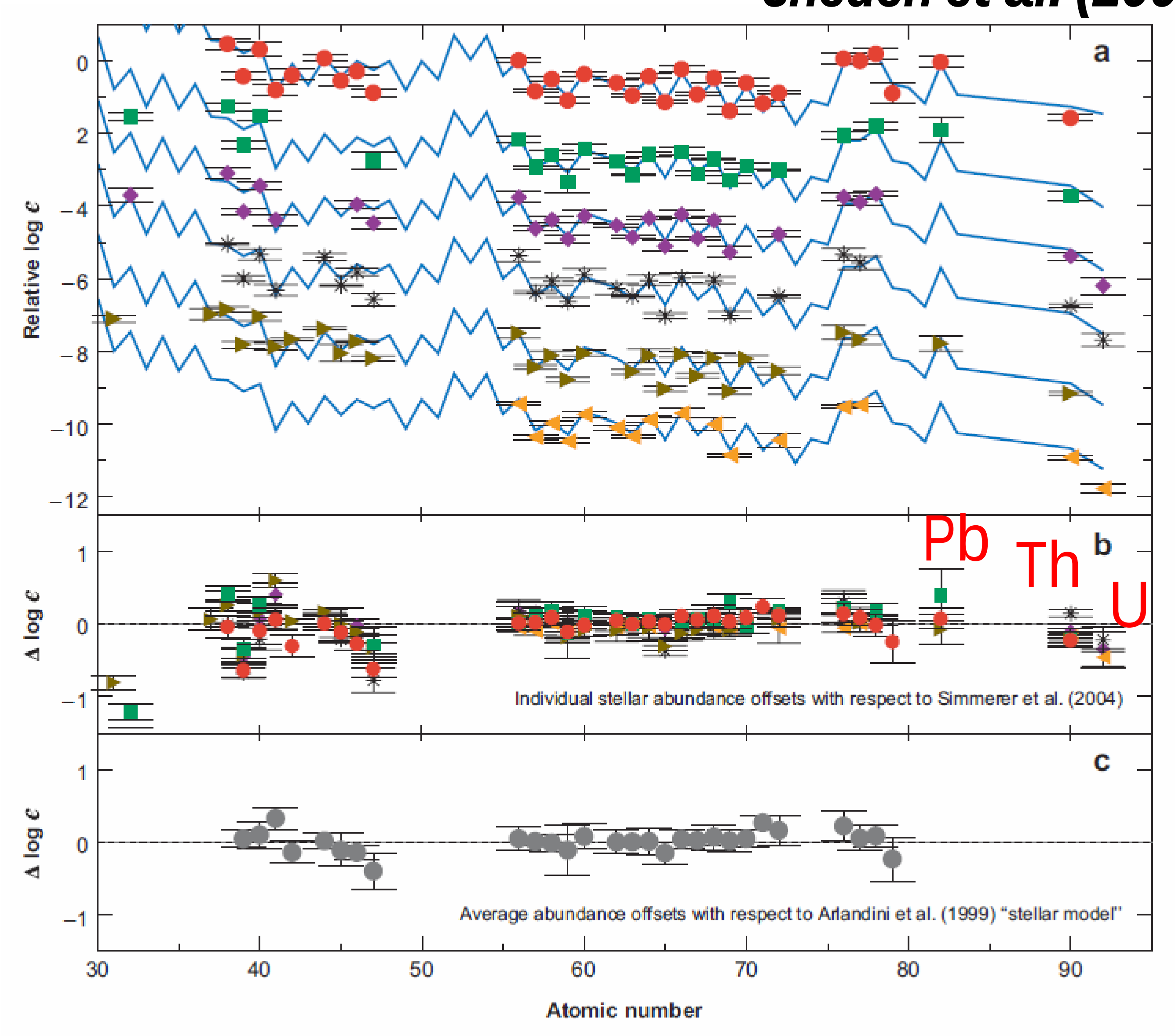
Roederer et al. (2012)



- Universality of heavy r-process elements?
- Diversity of light (weak) r-process elements?

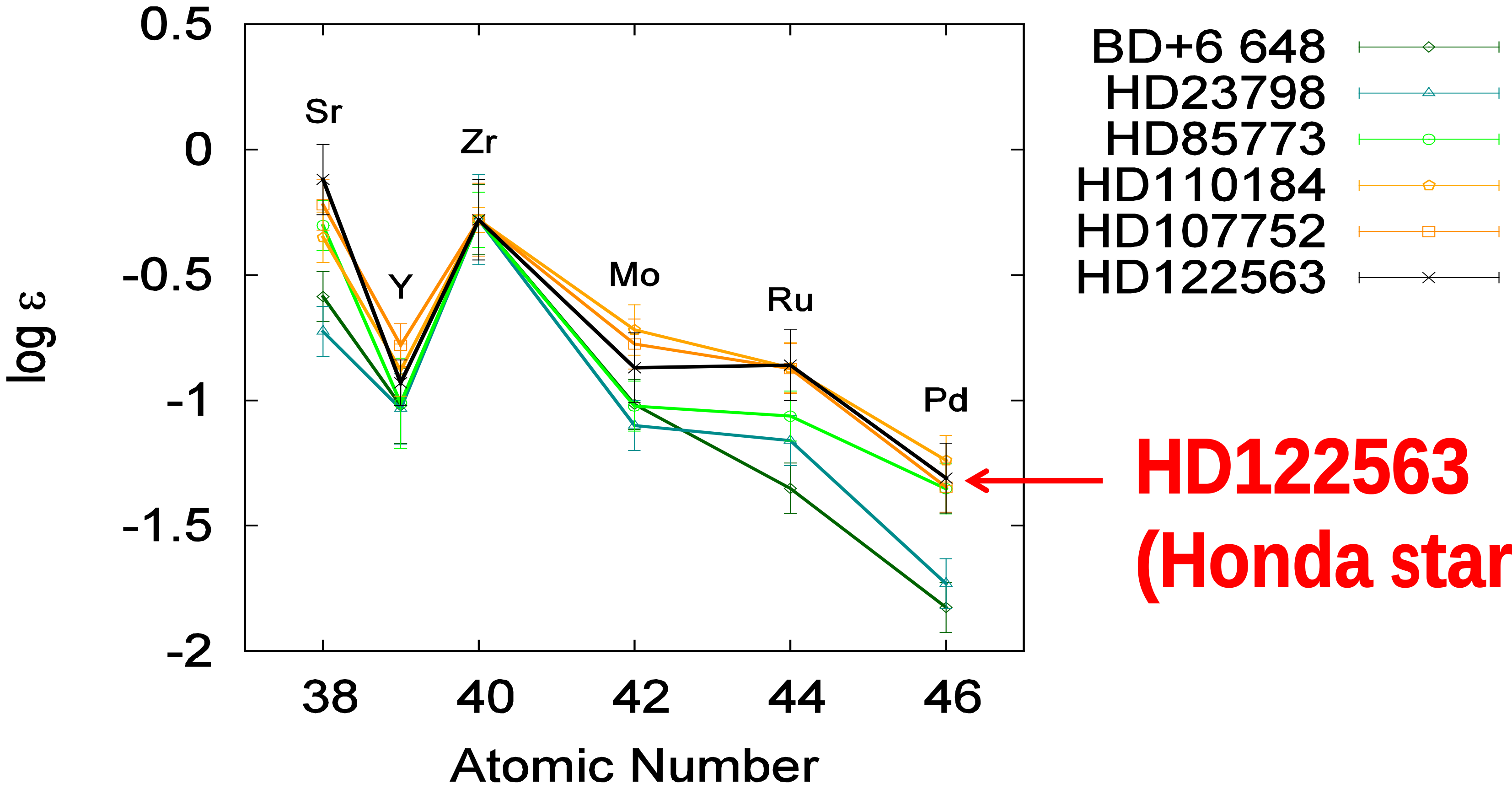
Universality of abundance patterns

Sneden et al. (2008, ARAA)



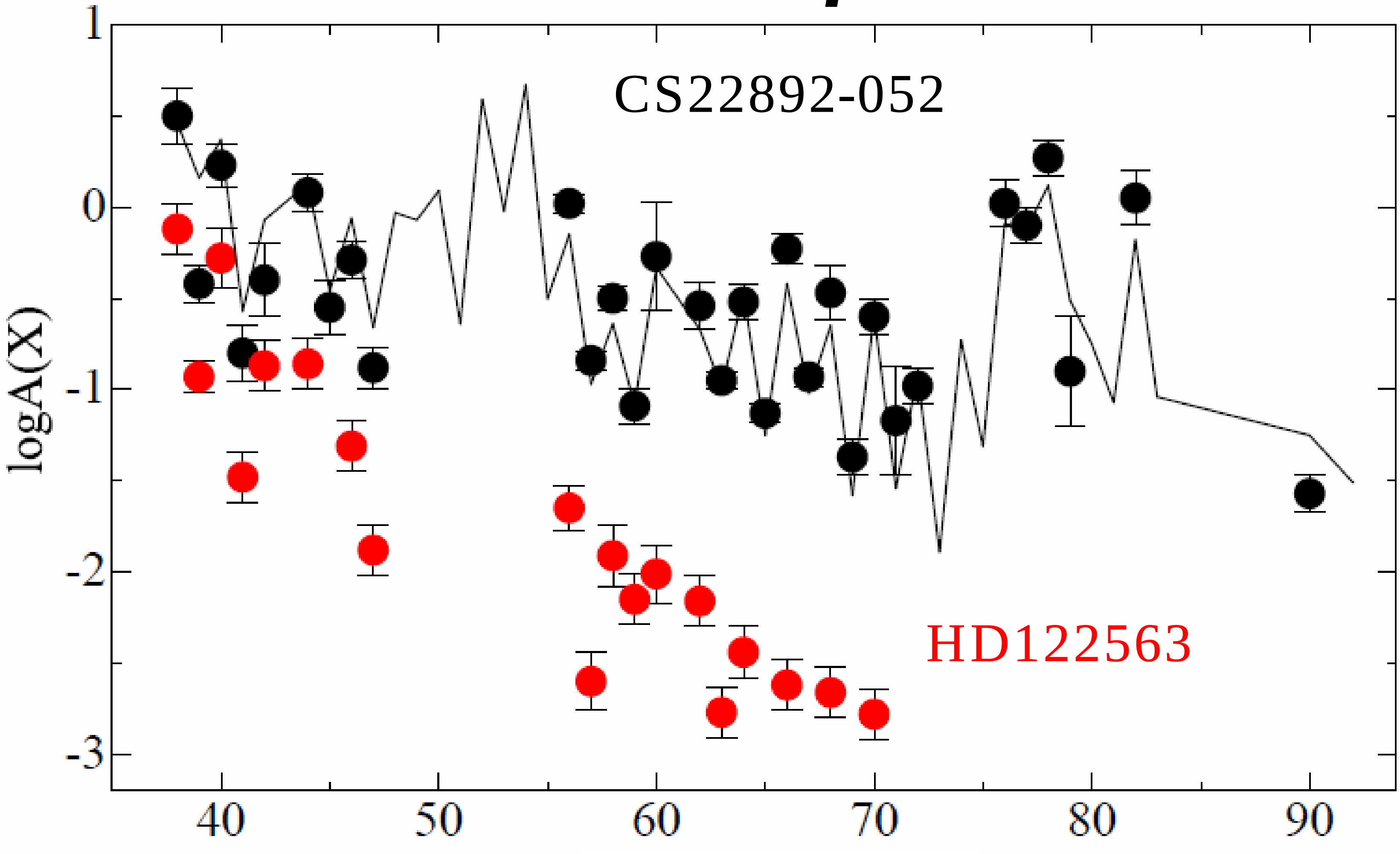
Diversity of abundance patterns produced by weak r-process?

M. Aoki et al., in prep.



HD122563
(Honda star)

"main" and "weak" r-process abundance pattern

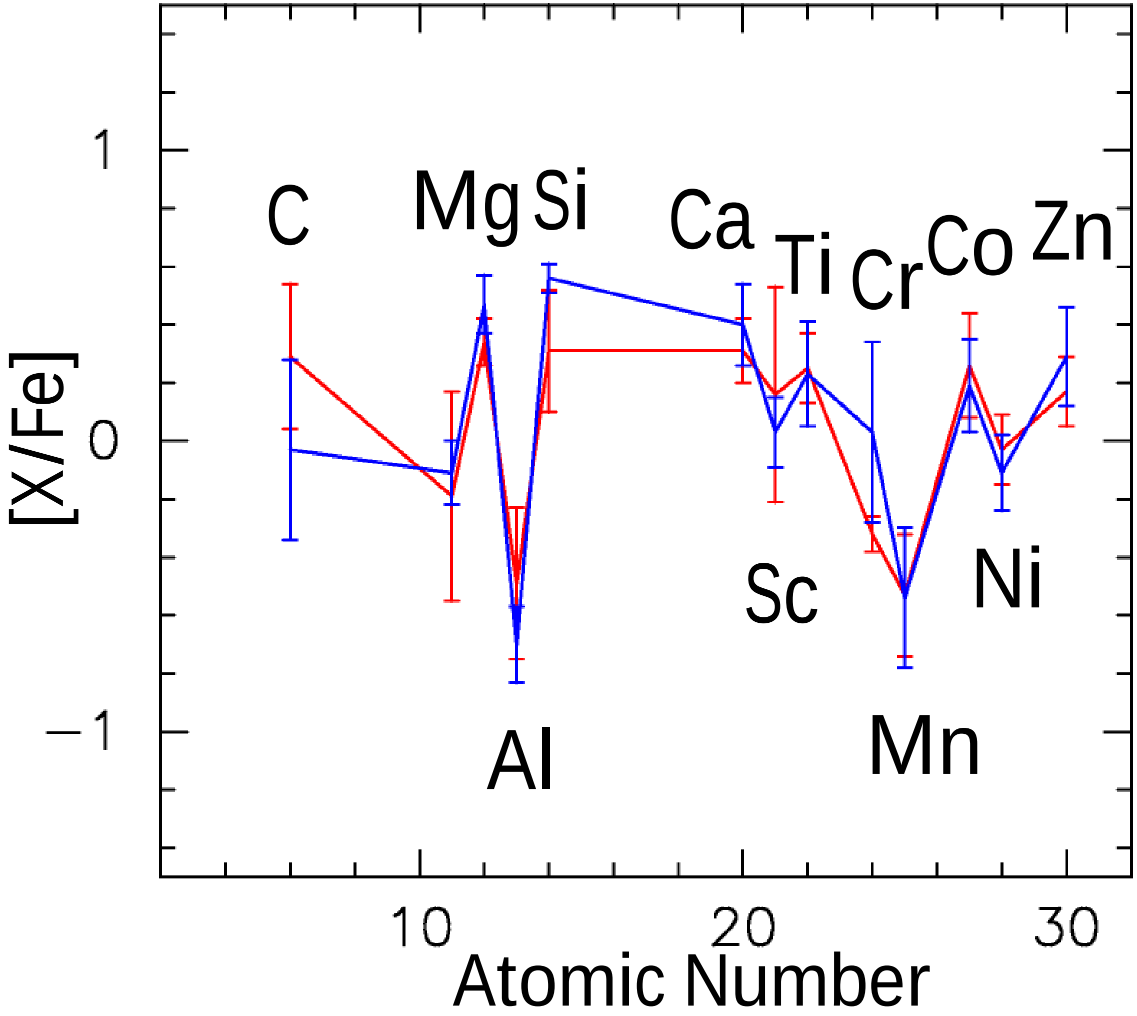


Atomic number

中性子捕獲元素の過剰（欠乏）と鉄より軽い元素の組成には相関なし（今のところ）

No correlation with lighter elements

(Is this still correct when the measurement quality is increased?)



R-process enhanced stars
[Eu/Fe]>+1.0 (9 stars)

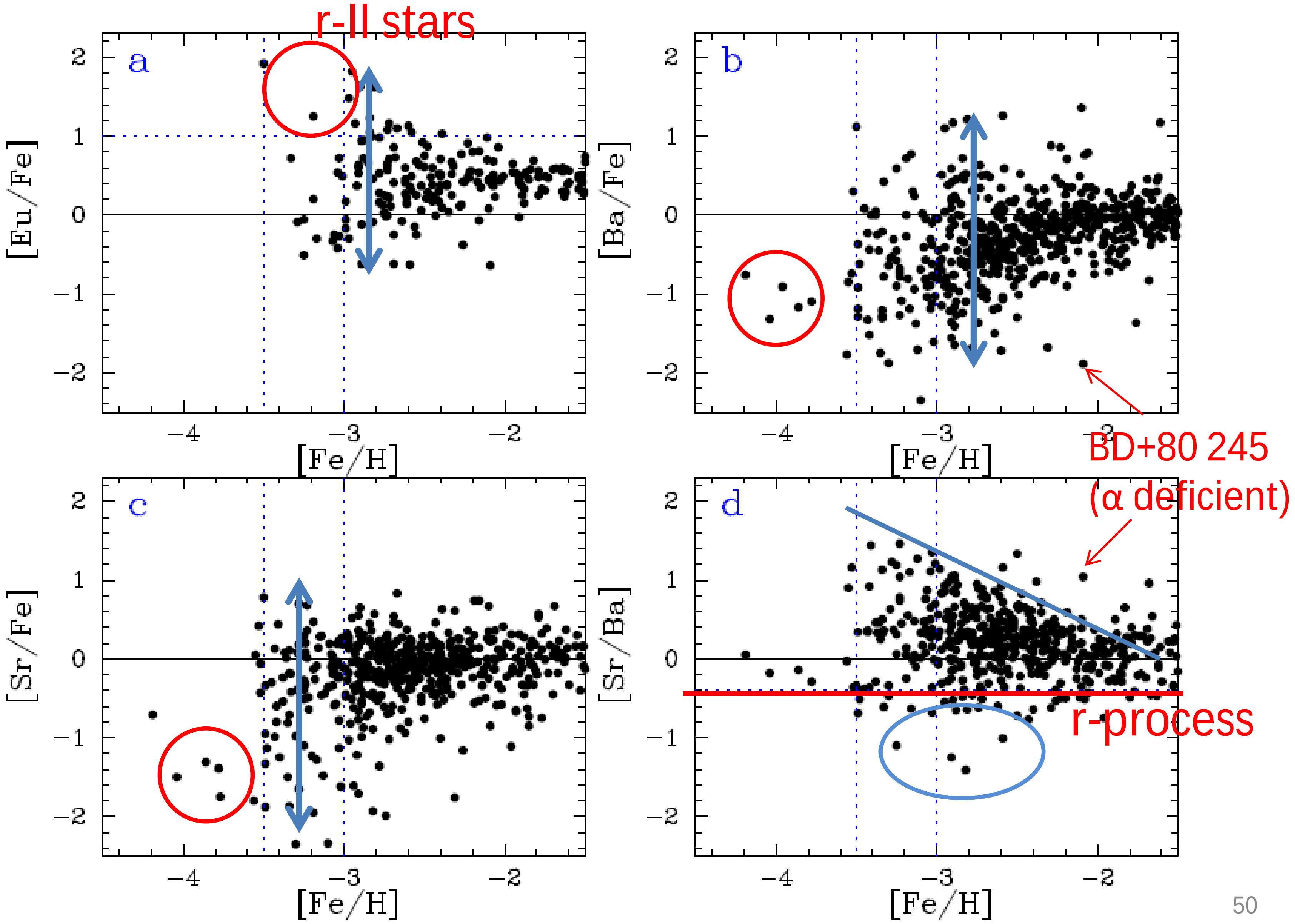
others
[Eu/Fe]<+0.5 (9 stars)

All stars are red giants
-3.2 < [Fe/H] < -2.6
4600K < Teff < 5200K

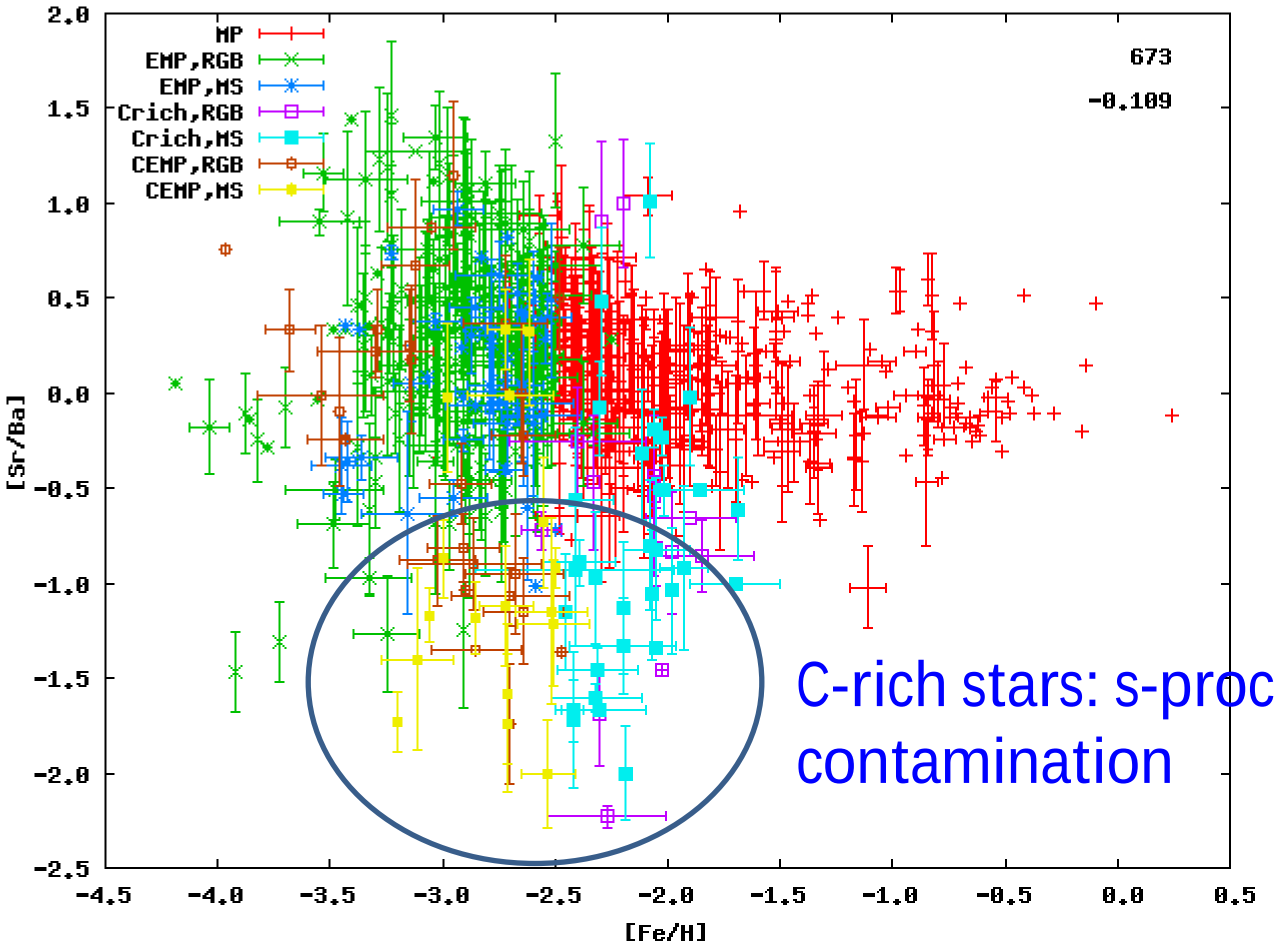
中性子捕獲元素の組成比には大きな分散

化学進化におけるr-process元素の立ち上がりと最も金属量の低い星のr-process元素

Sr and Ba (and Eu) abundance distributions

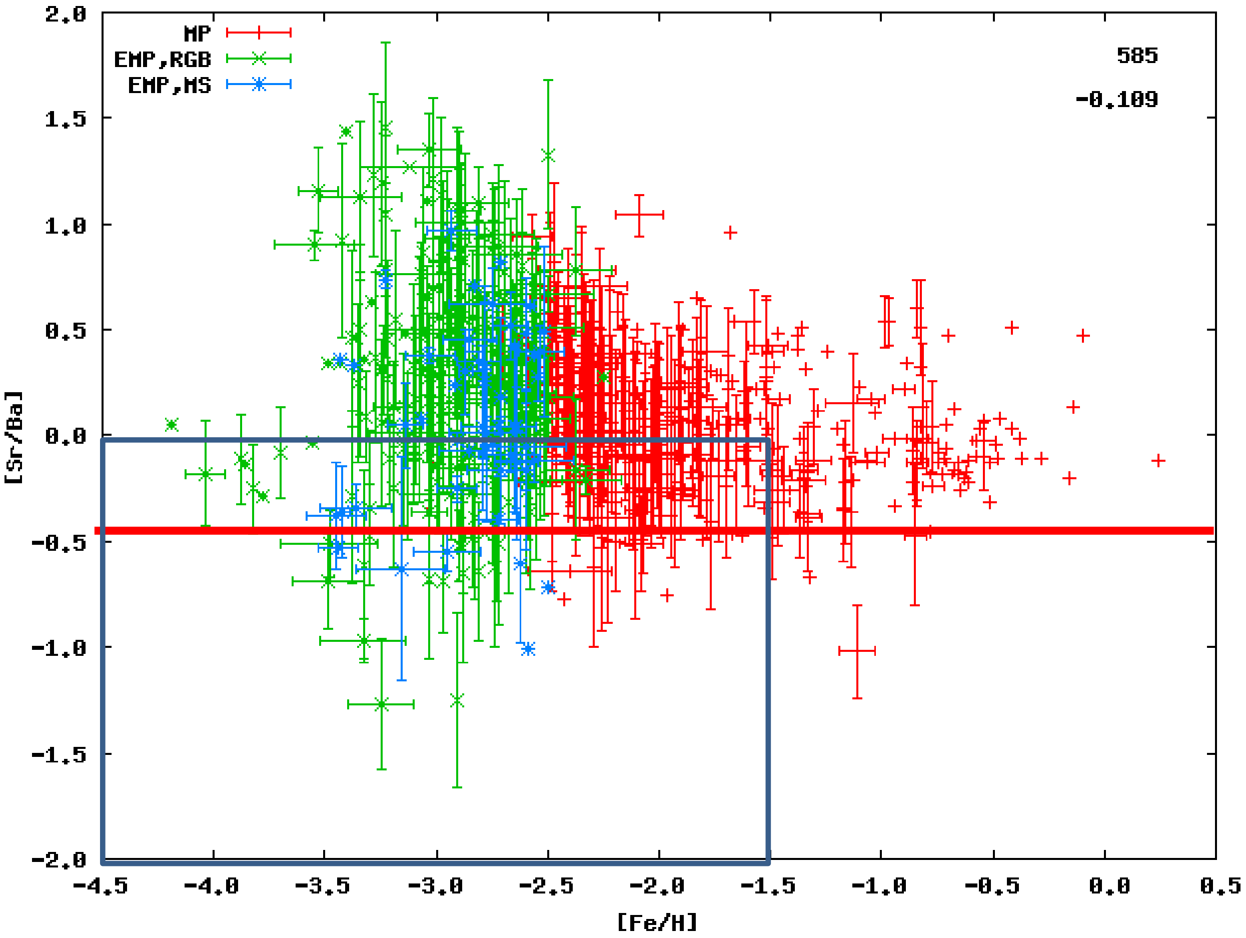


Low Sr/Ba stars

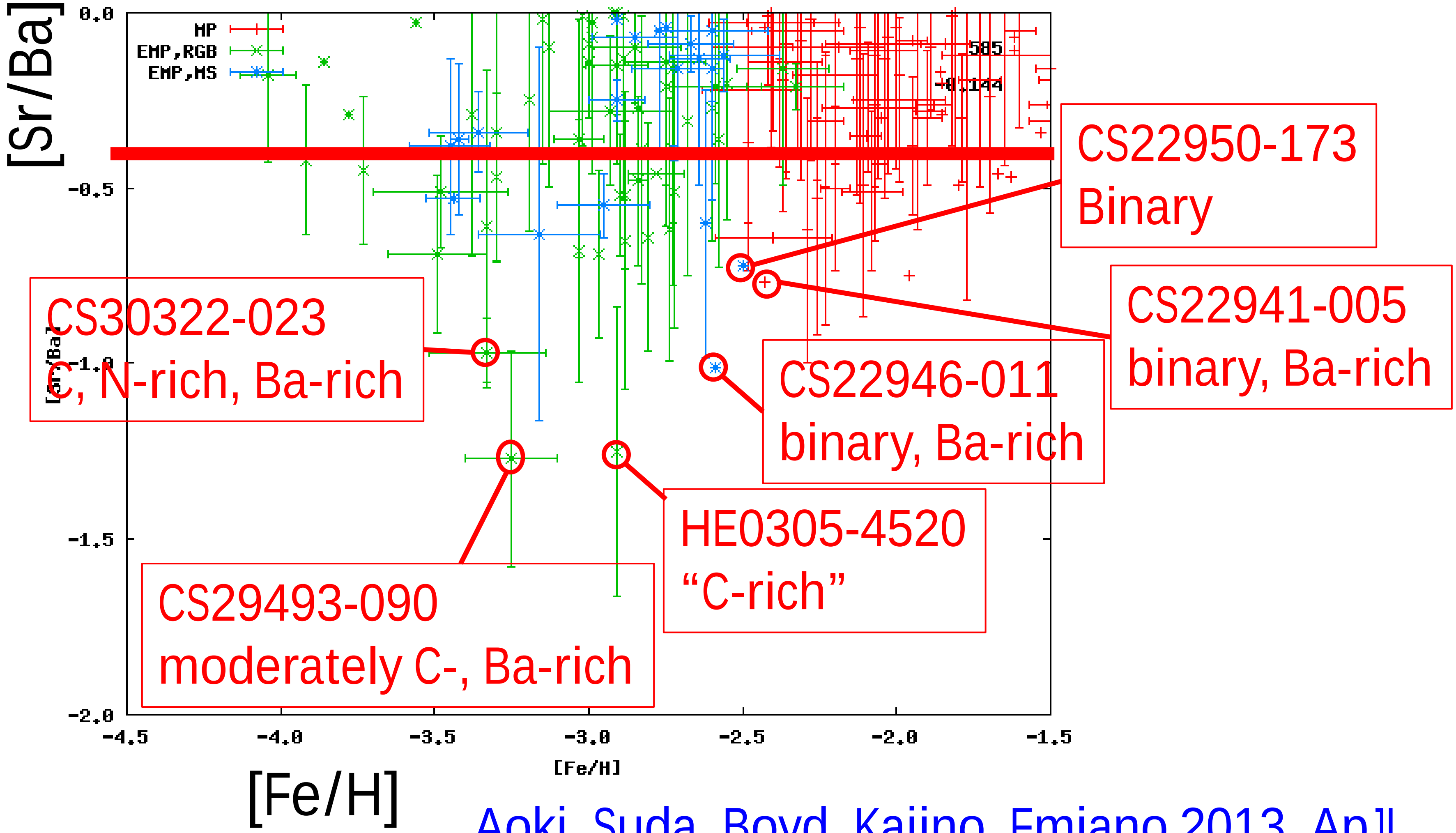


C-rich stars: s-process contamination

Low Sr/Ba stars



Low Sr/Ba stars



CS22950-173
Binary

CS30322-023
C, N-rich, Ba-rich

CS22941-005
binary, Ba-rich

CS22946-011
binary, Ba-rich

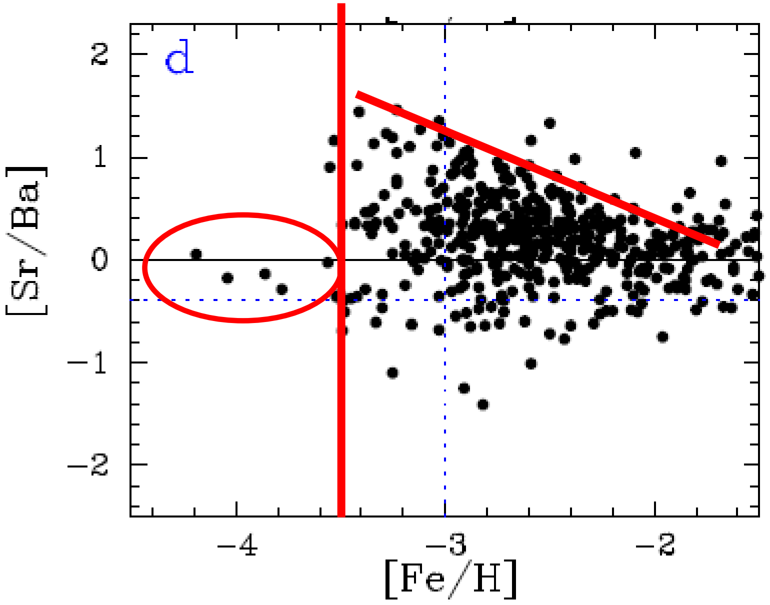
HE0305-4520
“C-rich”

CS29493-090
moderately C-, Ba-rich

Aoki, Suda, Boyd, Kajino, Fmiano 2013, ApJL

Questions about Sr and Ba abundances in very metal-poor stars

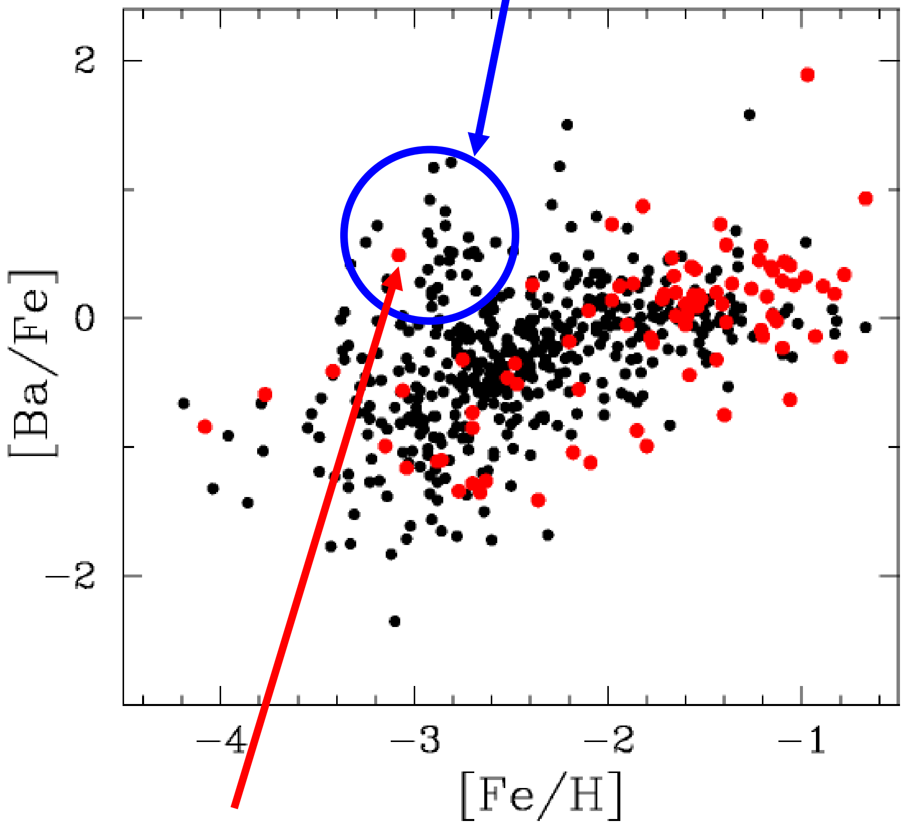
1. Existence (or absence) of the cut-off at [Fe/H]=-3.5, below which Sr and Ba abundance scatter is small.
2. Origin of (the small amount of) Sr and Ba in stars with [Fe/H]=-3.5: small yields by CCSN?
3. Reason for the upper bound in Sr/Ba distribution ([Sr/Ba]〜-1.5-[Fe/H])



矮小銀河〜
銀河系とは異なる化学進化の環境〜
での中性子捕獲元素

Neutron-capture elements in dwarf galaxies

r-process-enhanced stars in the Milky Way



●:dwarf galaxy stars
●:field stars

※carbon-enhanced stars are excluded
→Ba is mostly r-process origin

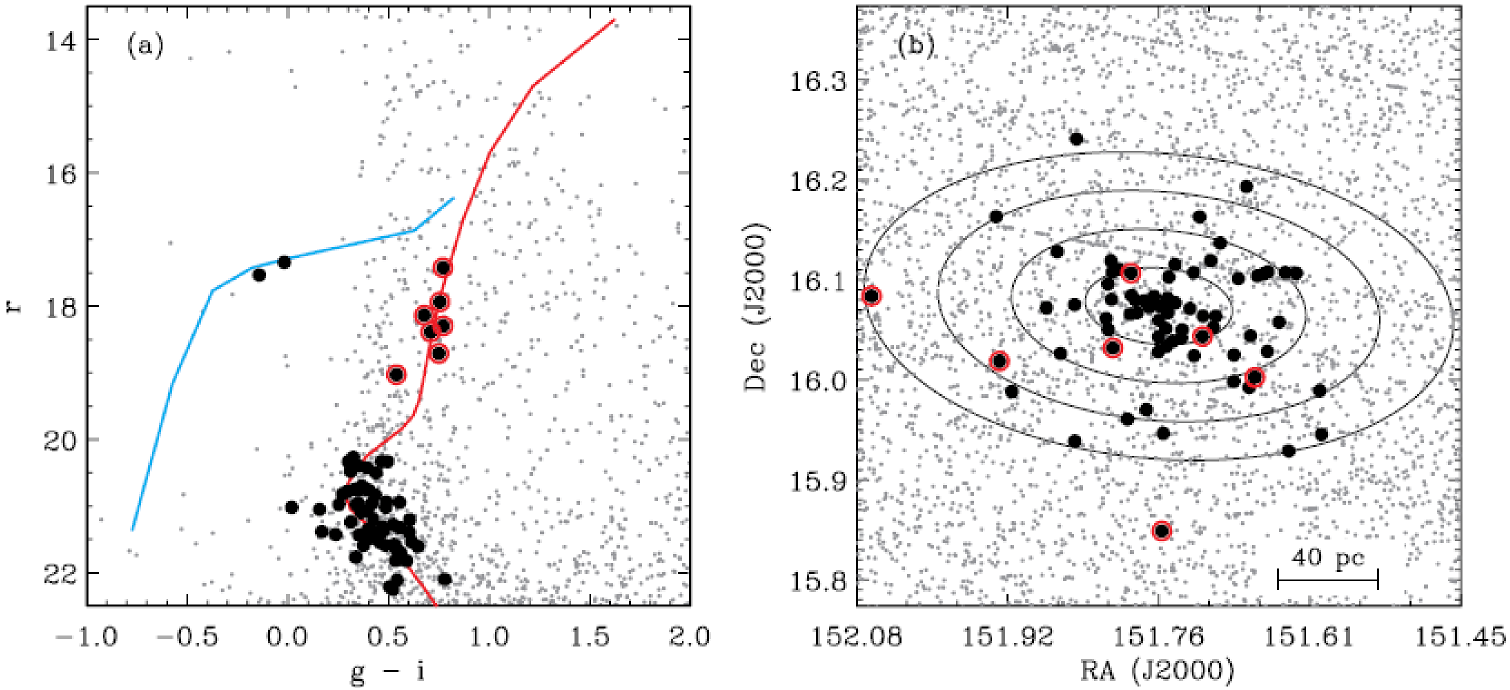
Ba is more under-abundant in dwarf galaxies
→no r-process-enhanced stars in dwarf galaxies?

The Ba of this object is attributed to s-process
(Honda et al. 2011)

The ultra-faint dwarf galaxy Segue 1

Frebel et al. (2014)

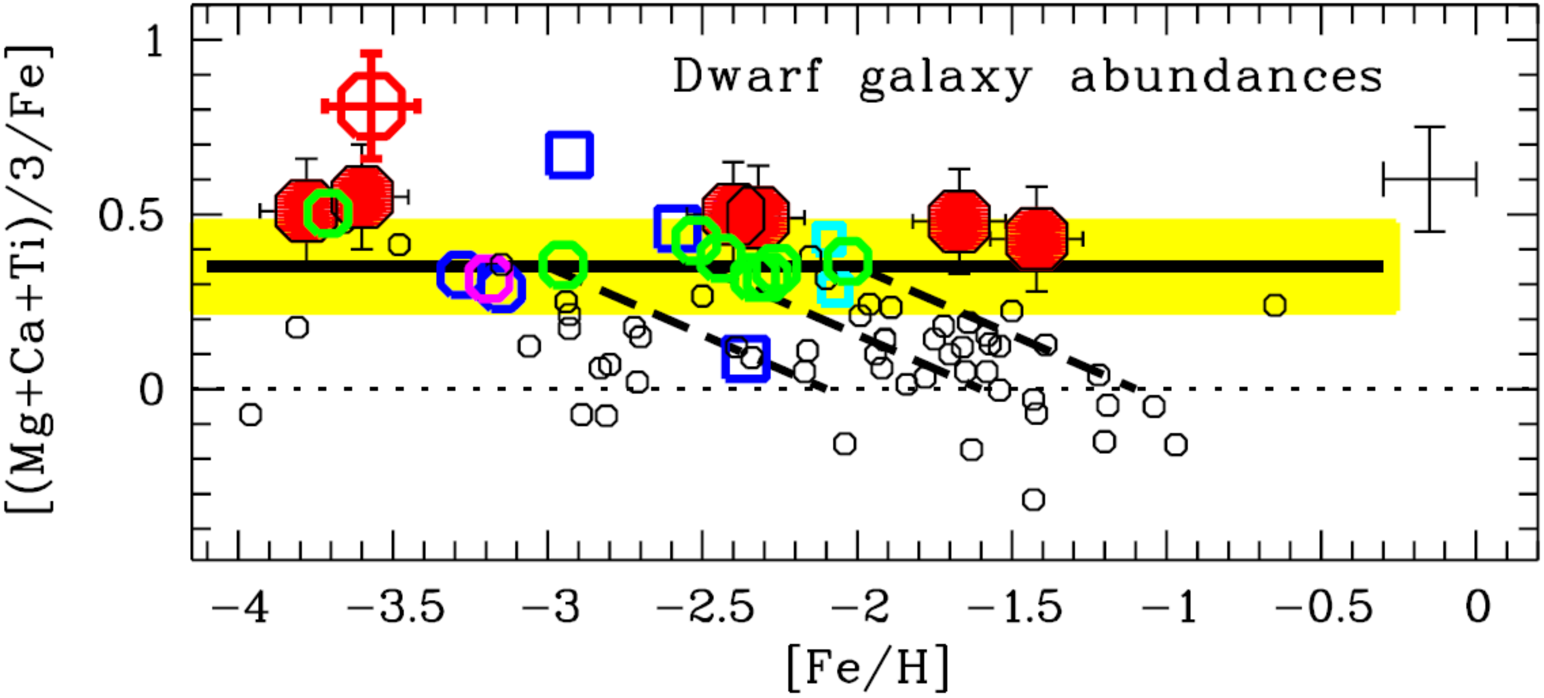
Only 7 red giants in the galaxy



The ultra-faint dwarf galaxy Segue 1

Frebel et al. (2014)

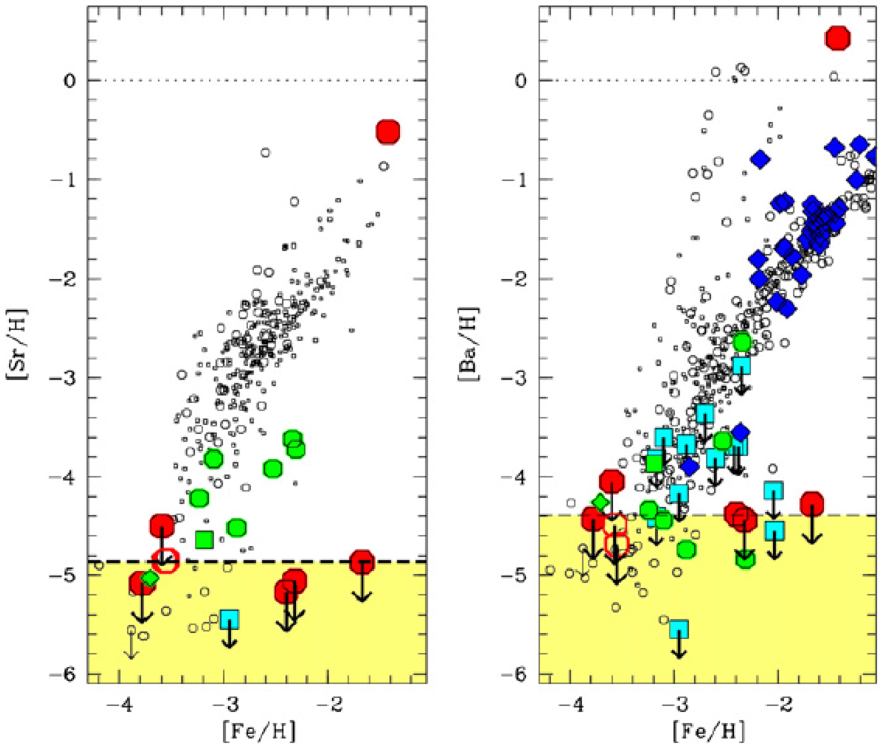
Constant α/Fe ratios → “one-shot enrichment”



The ultra-faint dwarf galaxy Segue 1

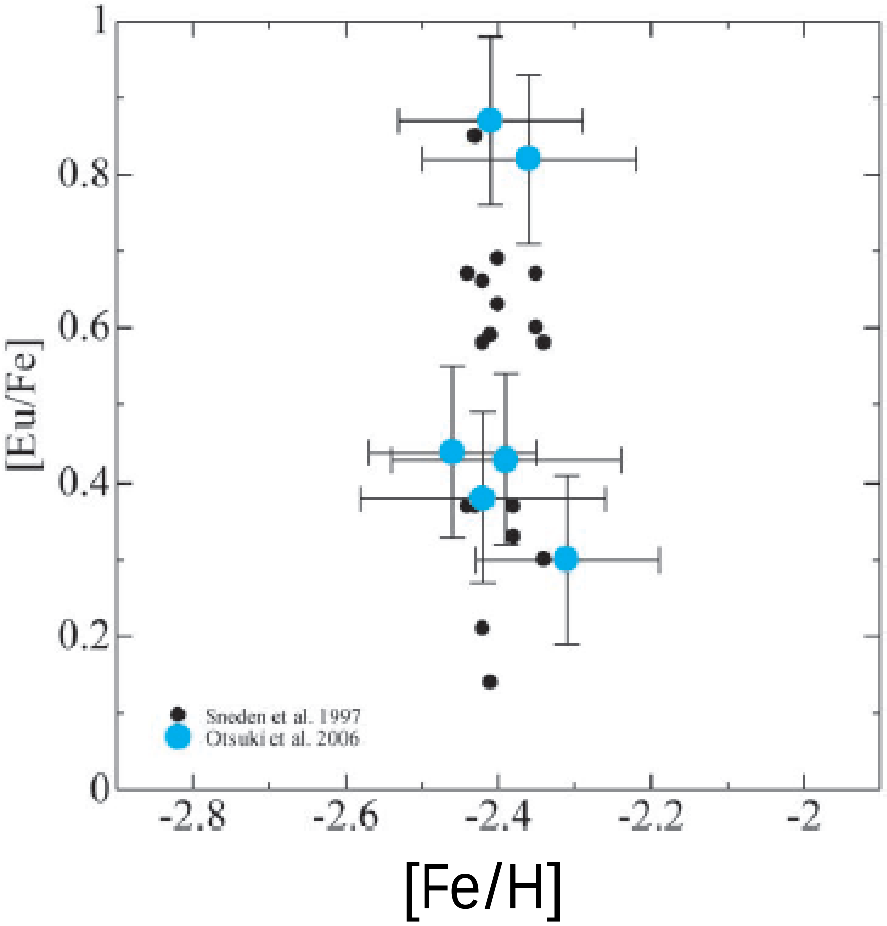
Frebel et al. (2014)

No detectable heavy elements



球状星団でも中性子捕獲元素の組成比に分散

Eu/Fe scatter in the globular cluster M15



Sneden et al. (1997) +
Otsuki et al. (2006)

Smaller scatter in [Sr/Fe],
[Y/Fe], and [Zr/Fe]

金属欠乏星観測の今後

- **金属欠乏星探査**
  -HK survey, Hamburg/ESO survey
  -SDSS/SEGUE
  -Skymapper (photometry)
  -LAMOST
  dwarf galaxies
- **フォローアップ分光**
  ～2025　8-10m class telescopes
  それ以降　TMT, GMT, E-ELT

Extension of the study with LAMOST and Subaru

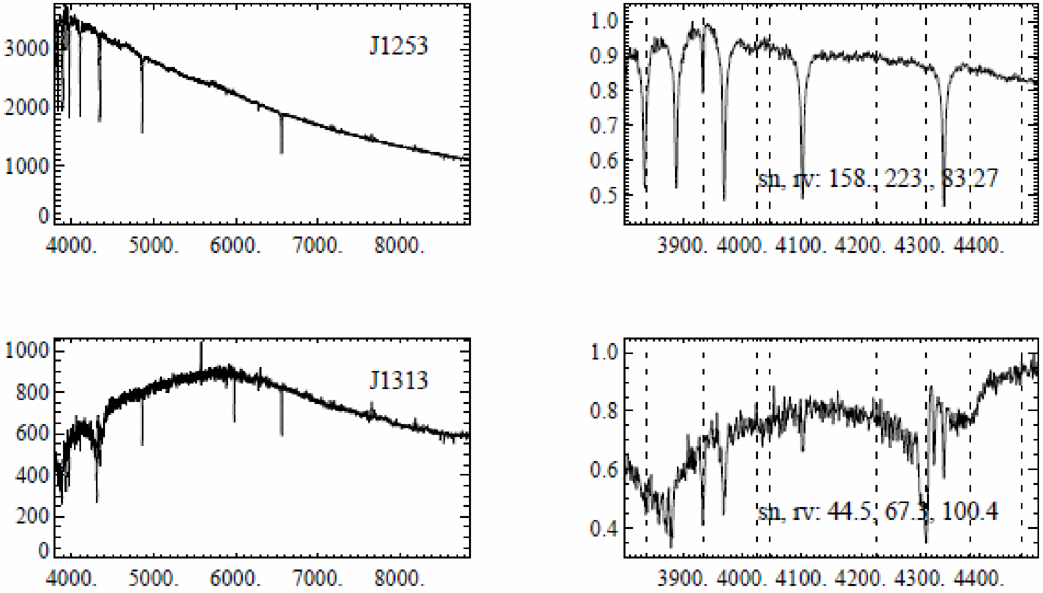
Aoki, Li, Zhao, Honda, Suda, Christlieb

Subaru/HDS follow-up spectroscopy for a large sample of candidate EMP stars found with LAMOST

LAMOST (**中国、興隆**)

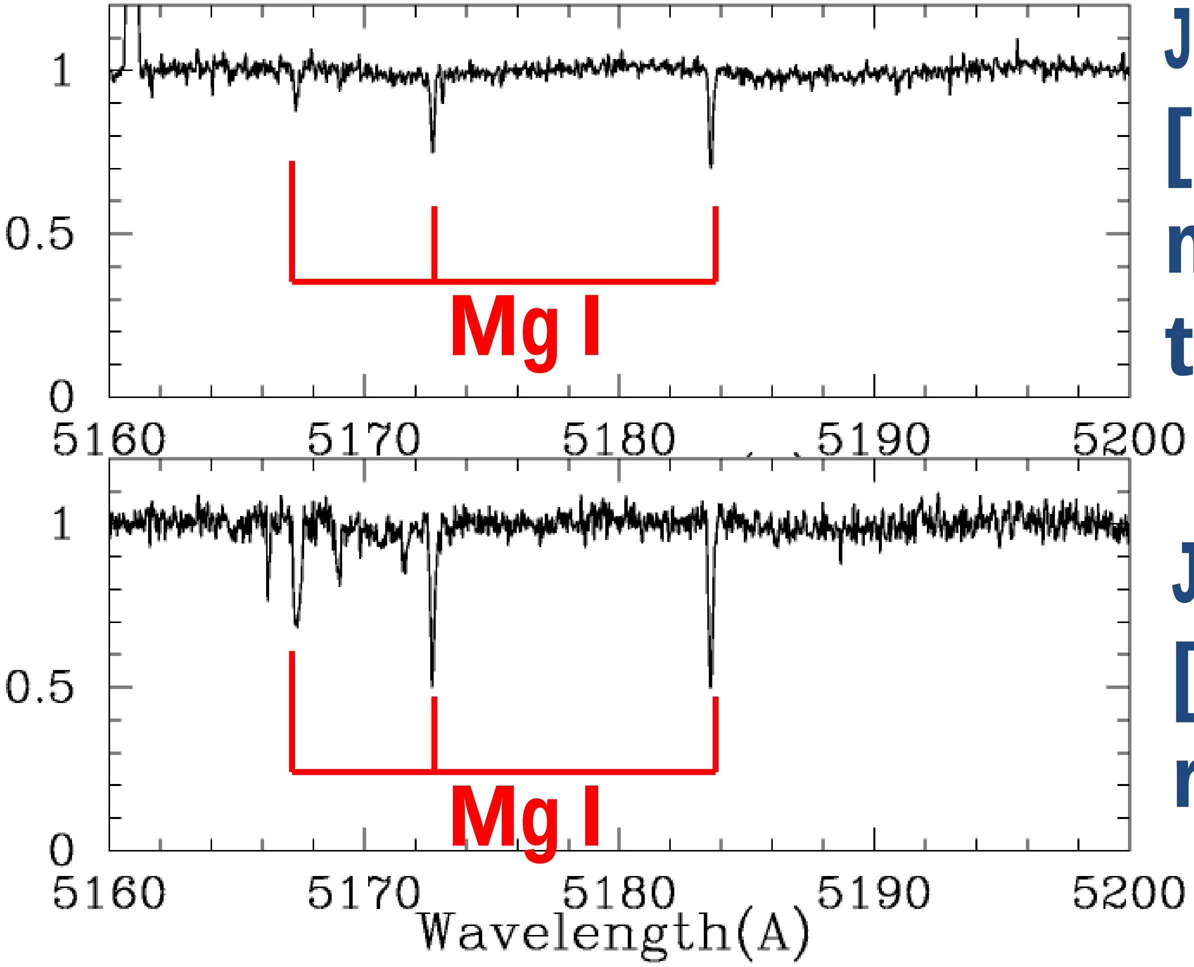
Target selection from LAMOST sample

LAMOST medium resolution spectra



Subaru high-resolution follow-up spectroscopy for 54 stars (May 2014, 2 nights)

High-resolution spectra obtained with Subaru/HDS (*R=36,000*)



J1253+0753
[Fe/H]=-4.0
main-sequence turn-off

J1313-0552
[Fe/H]=-4.0
red giant

Many stars with [Fe/H]<-3.5 from LAMOST/Subaru!

Li et al., preliminary results