NIC School
2023.9.12.

Astronomical Observations.
1. Stellar chemical compositions to constrain nucleosynthesis in the universe

Wako Aoki

National Astronomical Observatory of Japan

SOKENDAI (Graduate University for Advanced Studies)

Stellar chemical compositions to constrain nucleosynthesis in the universe

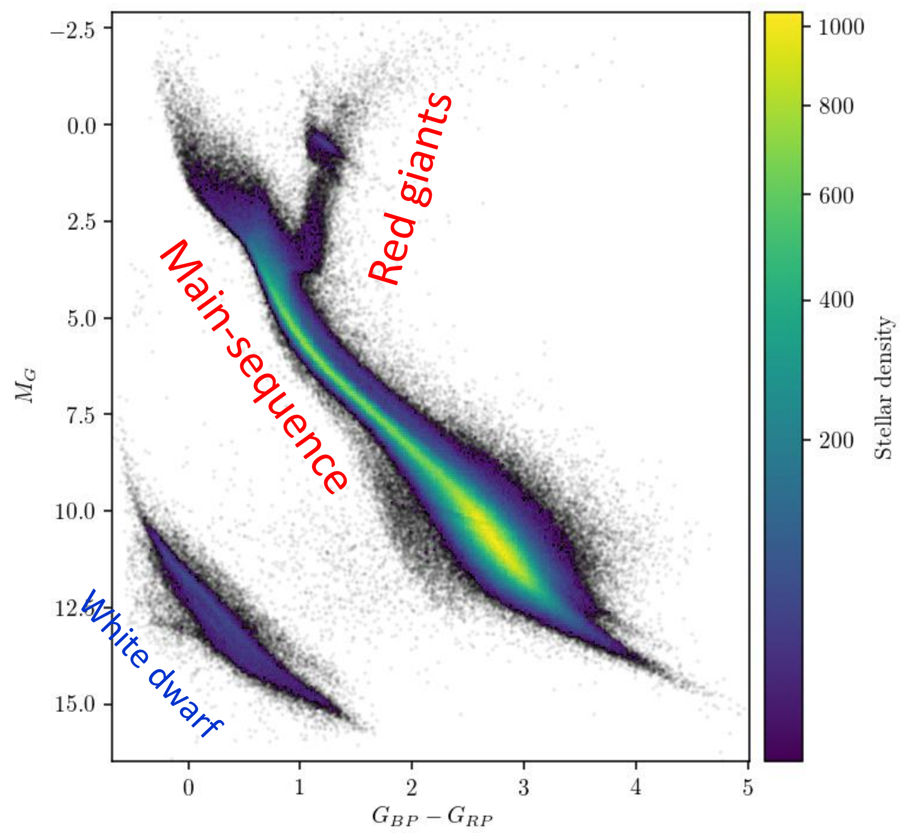
- **What can we know from chemical abundances of stellar surface?**

- **How are chemical abundances determined from stellar spectra?**

- **Which elements can we measure the abundances? How accurately can we measure?**

Stellar chemical compositions to constrain nucleosynthesis in the universe

- **Surface chemical abundances of stars**
- **Measurement of stellar chemical composition**
- **Reliability and uncertainty**
- **Solar chemical composition**
- **Isotope abundances**

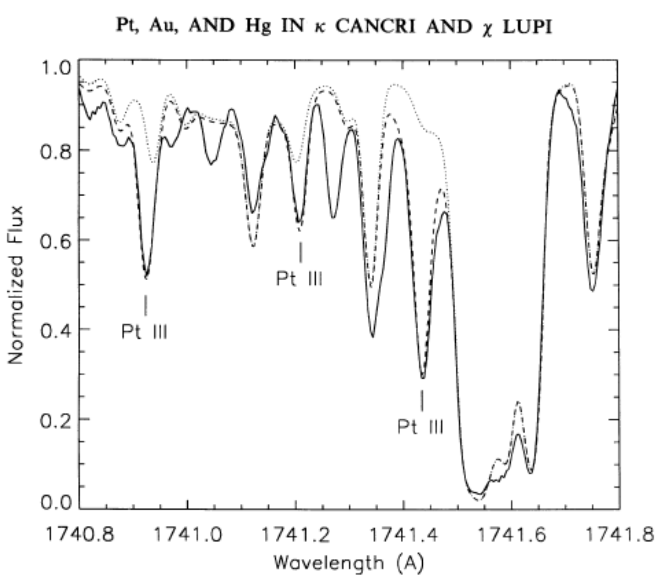


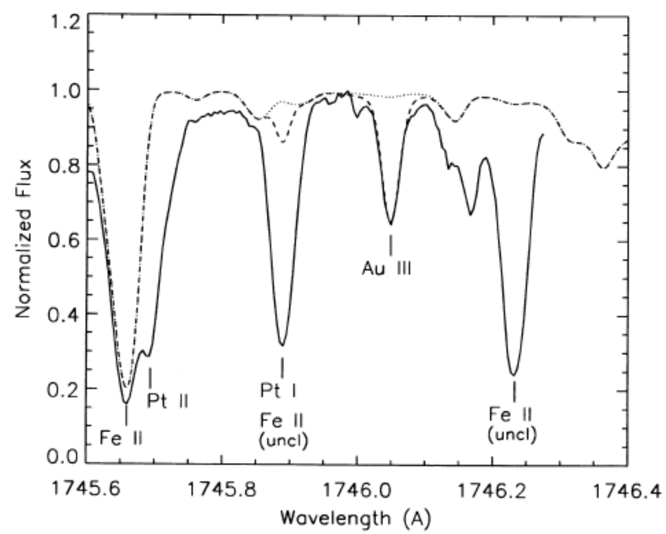
Color-Magnitude Diagram obtained with Gaia

Surface chemical abundances of stars

Chemical composition is regarded to be (almost) homogeneous in the surface (photosphere) in low-mass main-sequence (Solar-type) stars and red giants due to surface convection.

Exception: “Chemically peculiar stars” that have very thin surface convection zone (+ having strong magnetic field?)



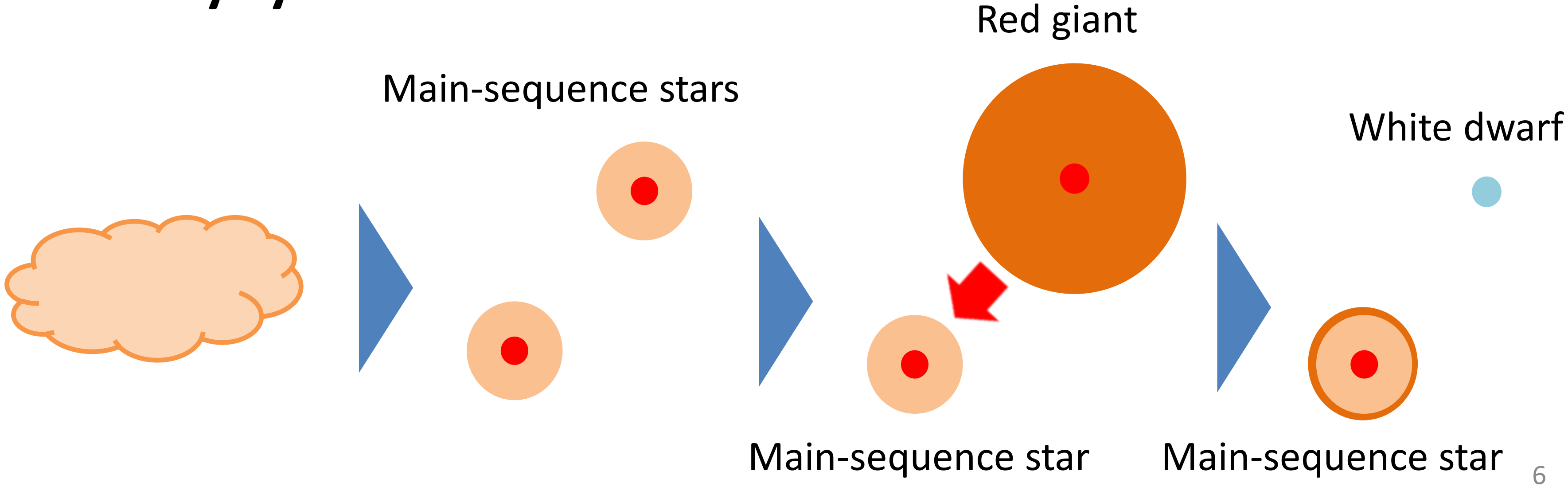


Wahlgren et al. (1995)

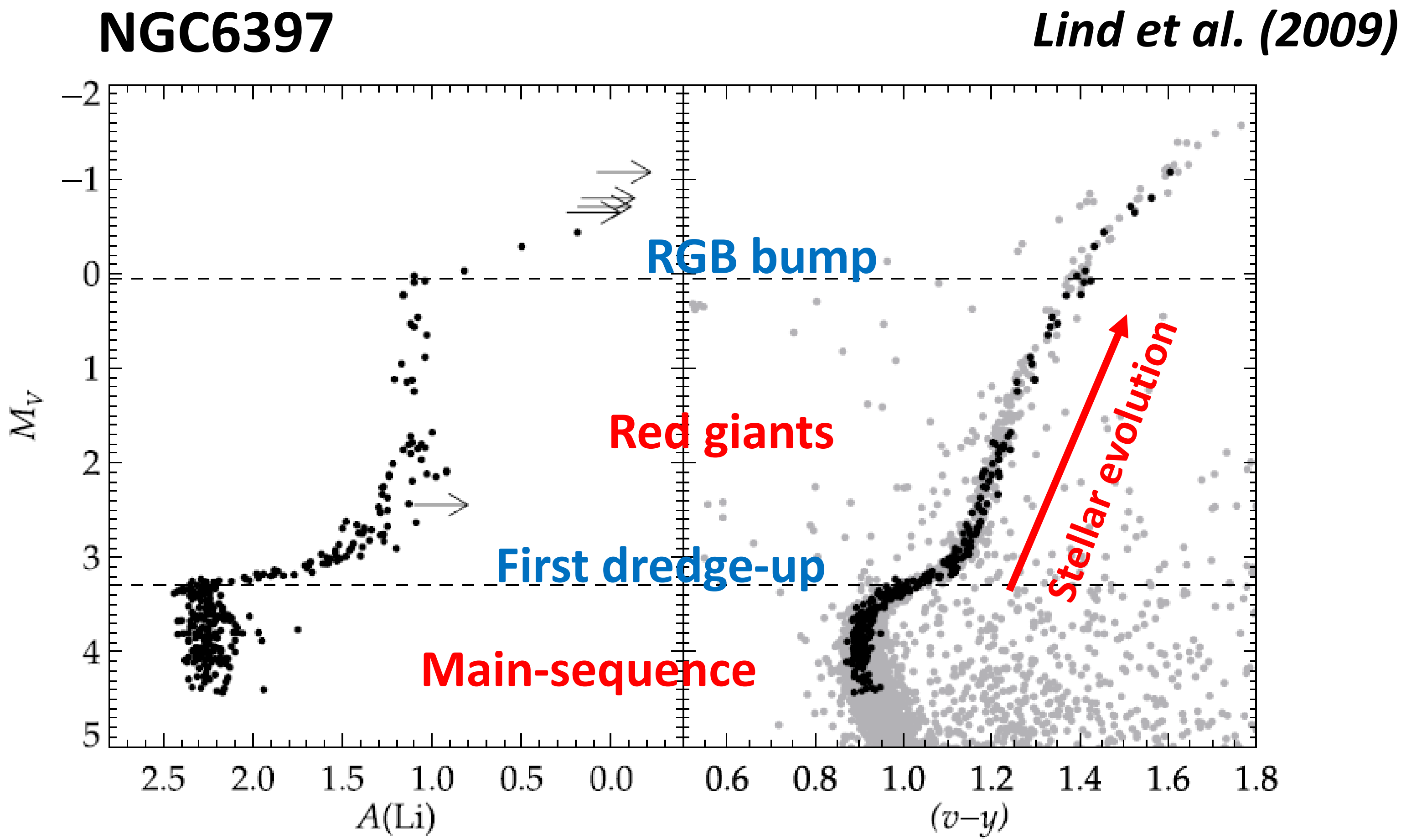
Surface chemical abundances of stars

Composition in the cloud from which the star formed
+ internal process/mixing
+ interaction with companions/planets

- **Red giants/supergiants: affected by mixing with products of internal nucleosynthesis (ex. CNO cycle)**
- **Mass accretion from companion can be effective in binary systems**



Li abundance in globular cluster red giants



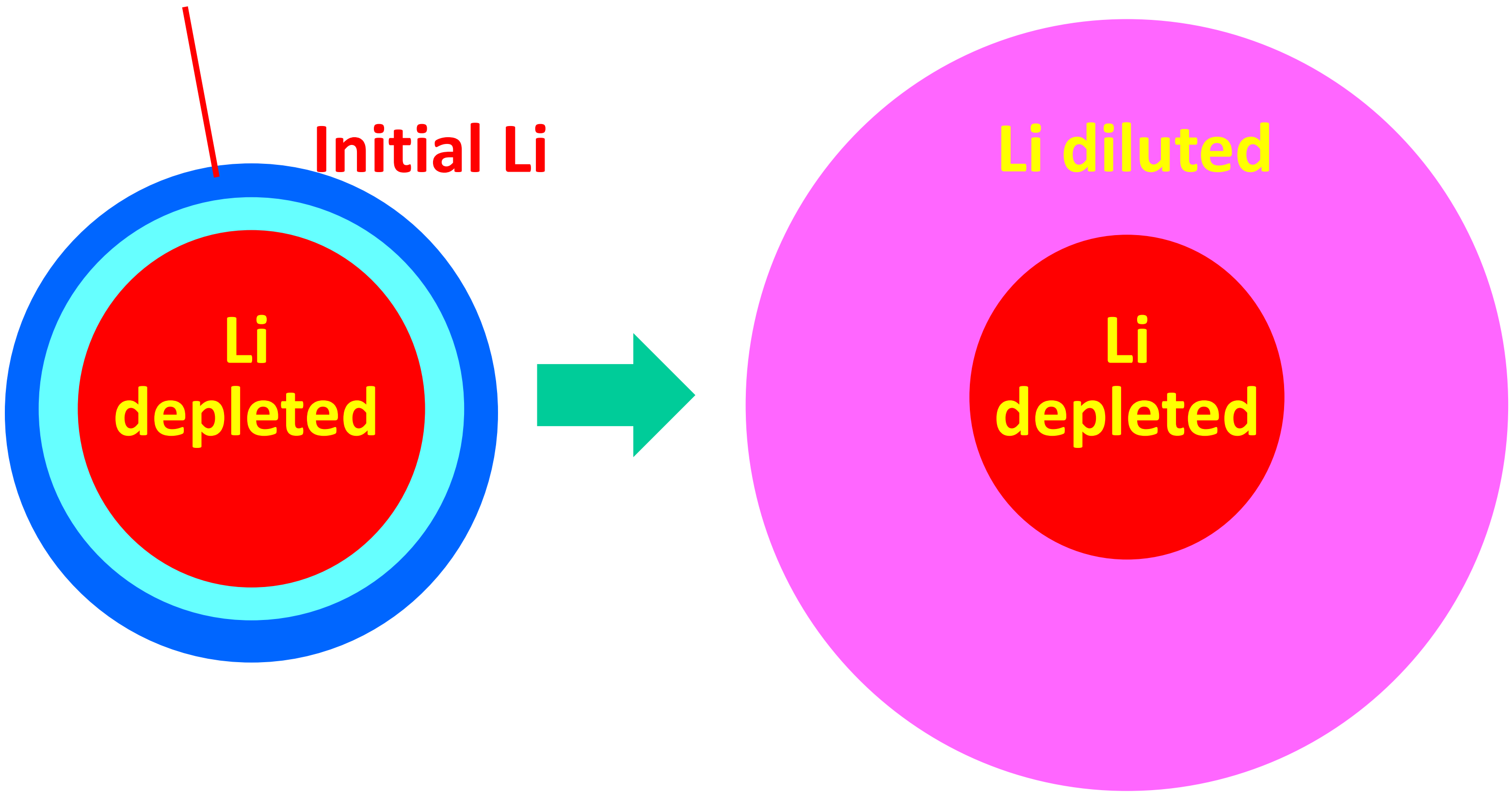
Lithium in very metal-poor stars

Main-sequence

shallow convective layer preserving initial Li abundance

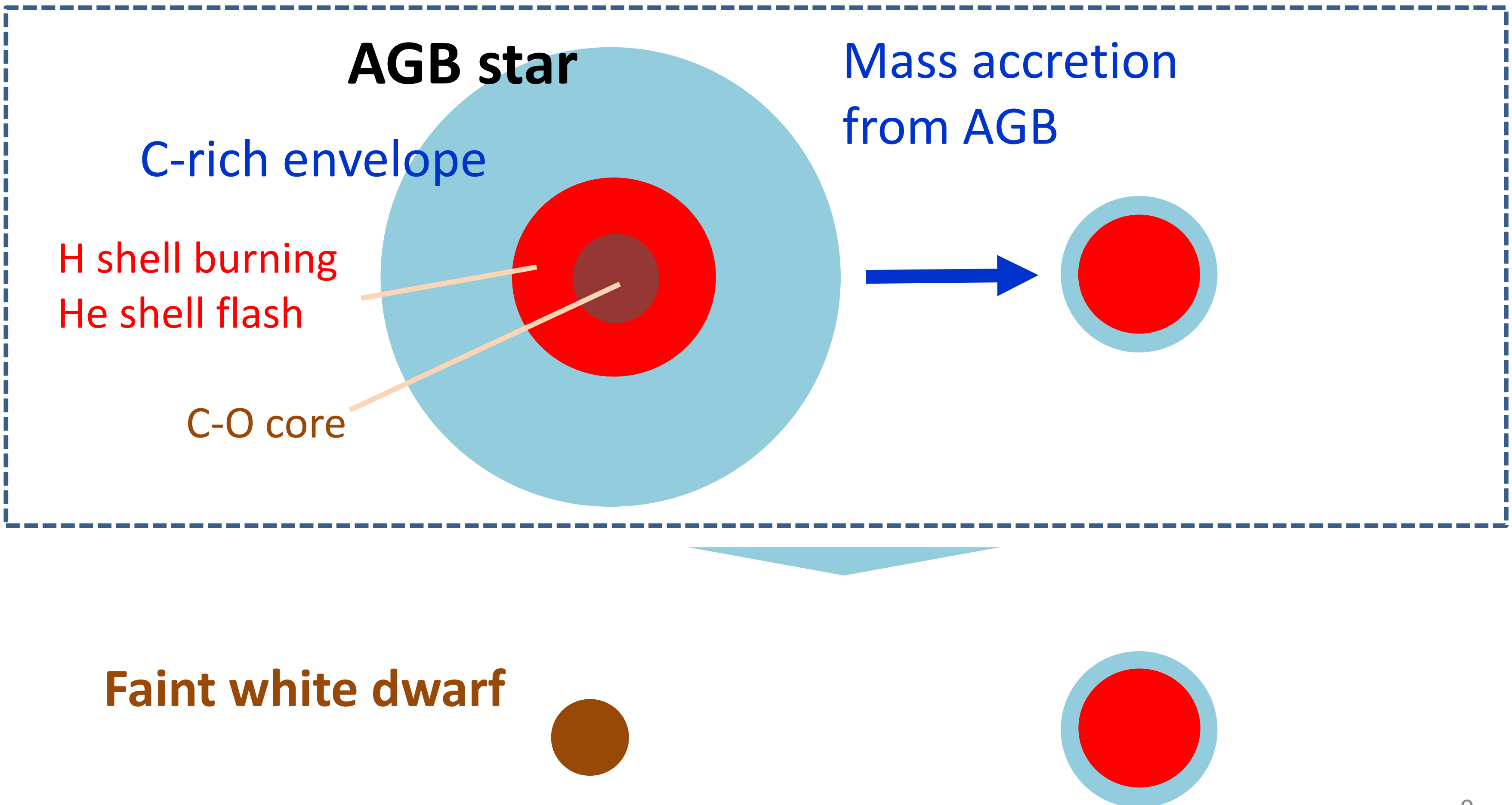
Red giants

Surface Li diluted by the internal material due to *1st dredge-up*



Interaction between stars in binary systems
Increase of carbon and s-process elements

AGB: Asymptotic Giant Branch



CEMP=Carbon-Enhanced Metal-Poor stars

- Carbon-enhanced stars in the Galactic halo are known as the spectral class CH stars (Keenan 1942).
- A number of carbon-enhanced stars were identified by the HK survey (e.g. *Beers et al. 1992*)

- The fraction of CEMP is estimated to be 10-25% in [Fe/H]<-2.
- Many of them are confirmed to belong to binary systems from radial velocity variations.

Beers et al. (1992)

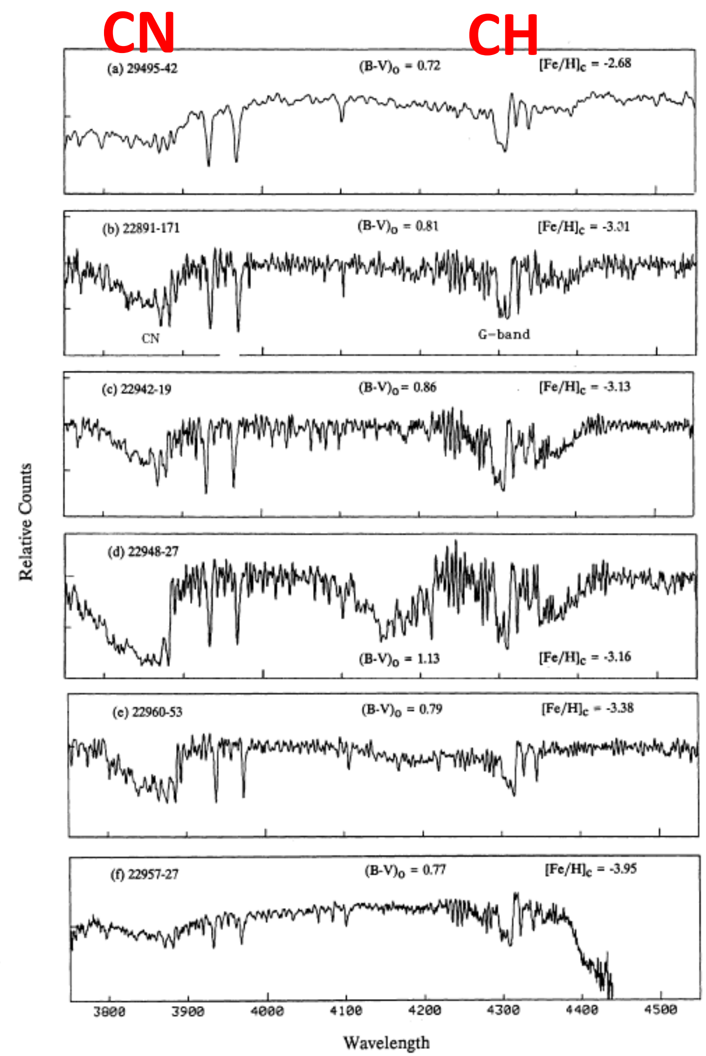


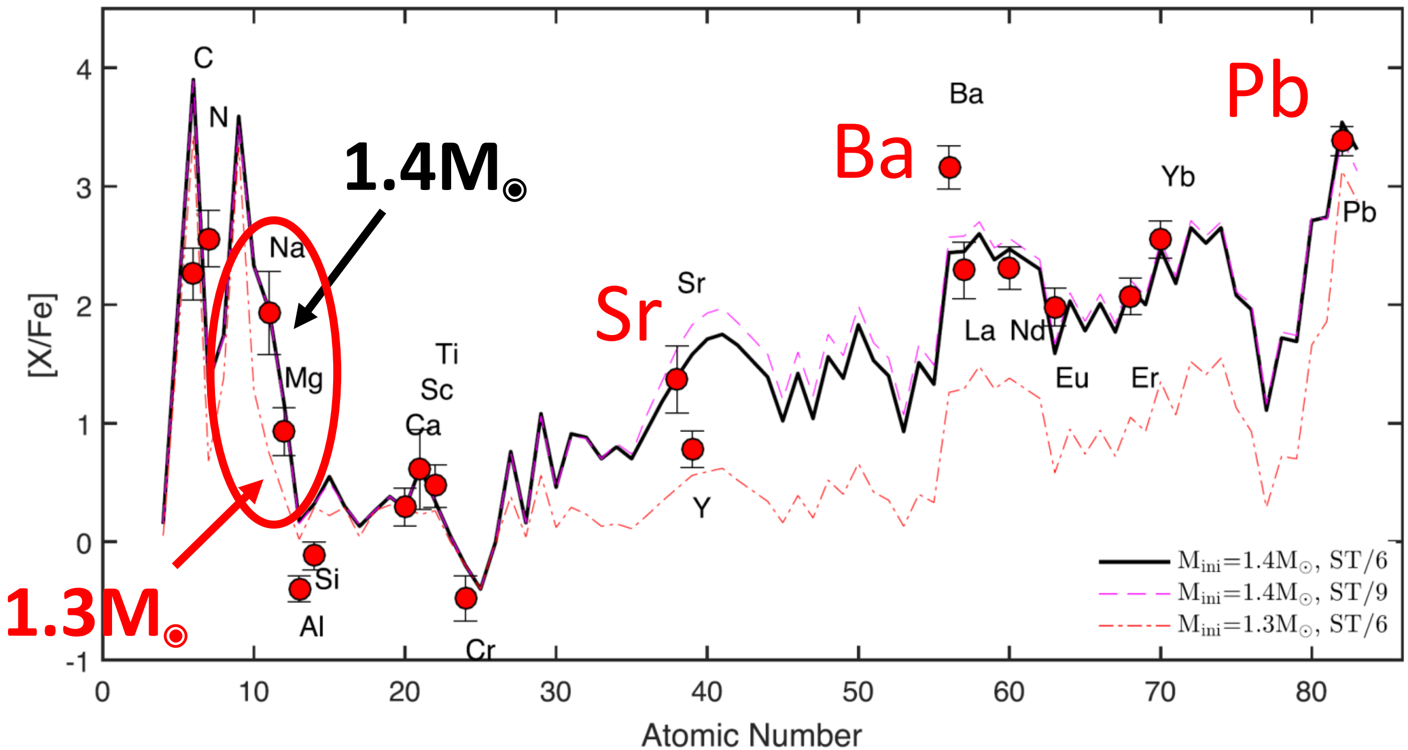
FIG. 13. Type examples of stars in the present sample with moderate to strong CN bandheads at λ3883 Å and/or λ4215 Å, and anomalously large CH (*G*-band) λ4300 Å features. All spectra have been smoothed with a Gaussian of breadth 2.5 Å, and flattened with a boxcar smooth.

Comparison with AGB nucleosynthesis models

Direct comparison of AGB models (e.g. Bisterzo et al. 2010)

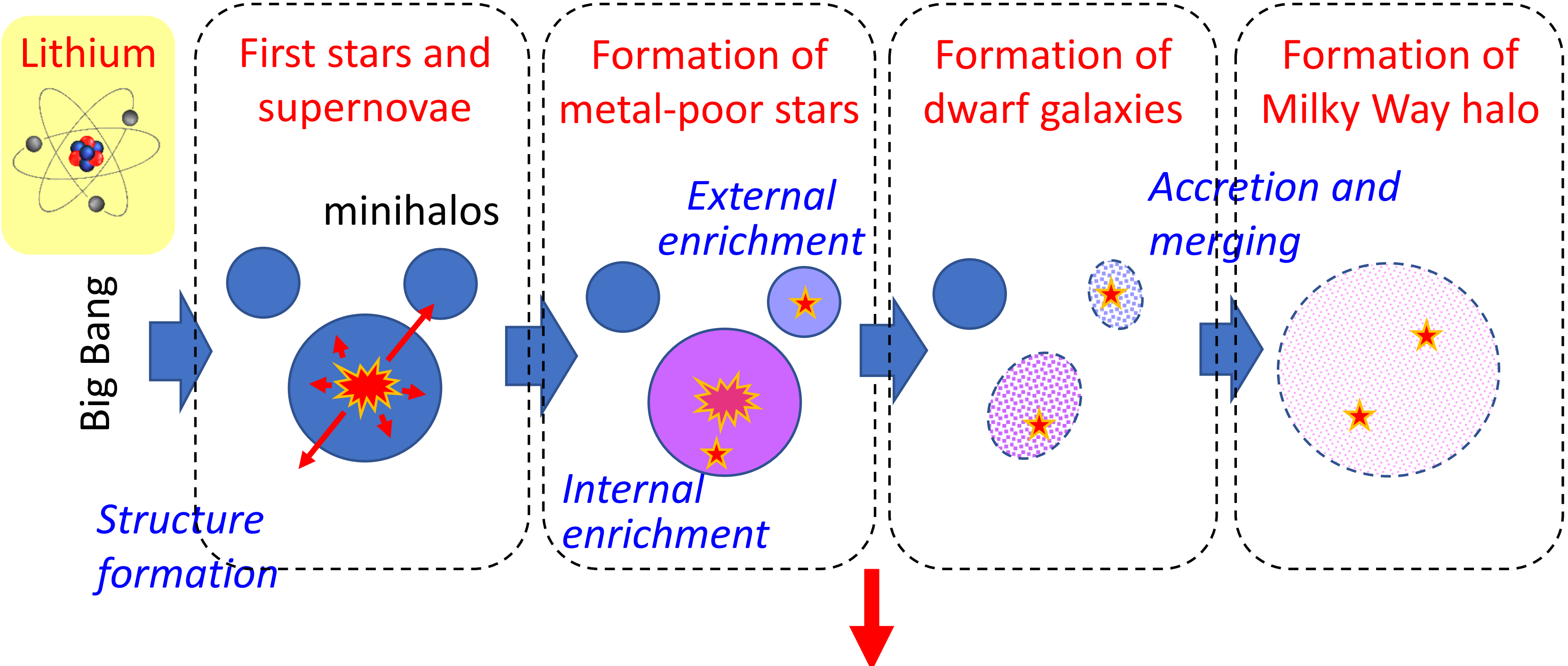
- Abundance pattern of neutron-capture elements (Sr-Ba-Pb) are reproduced by models of s-process for low metallicity
- Na and Mg abundances are useful to constrain AGB mass.
  →1.4M$_\odot$ model AGB star

Zhang et al. (2019)



Nucleosynthesis yields constrained from chemical composition

Nucleosynthesis of first generations of stars and their mass



Chemical abundances of extremely metal-poor stars
→ Nucleosynthesis of first stars/supernovae
→ Masses of progenitor stars
Understanding of evolution of metal-poor (low-mass) stars is needed.

Measurements of stellar chemical composition

- **Method**
  - **Measurement of spectral lines**
  - **Stellar atmosphere**
- **Reliability and uncertainty**
- **Chemical property and abundance measurement**
- **Solar abundances**
- **Isotope abundances**

Definition

- **Chemical abundance** : abundance ratio with respect to H

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

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

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

  例 : $[Fe/H]=-2.0$ → 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]

Solar abundance table (example)

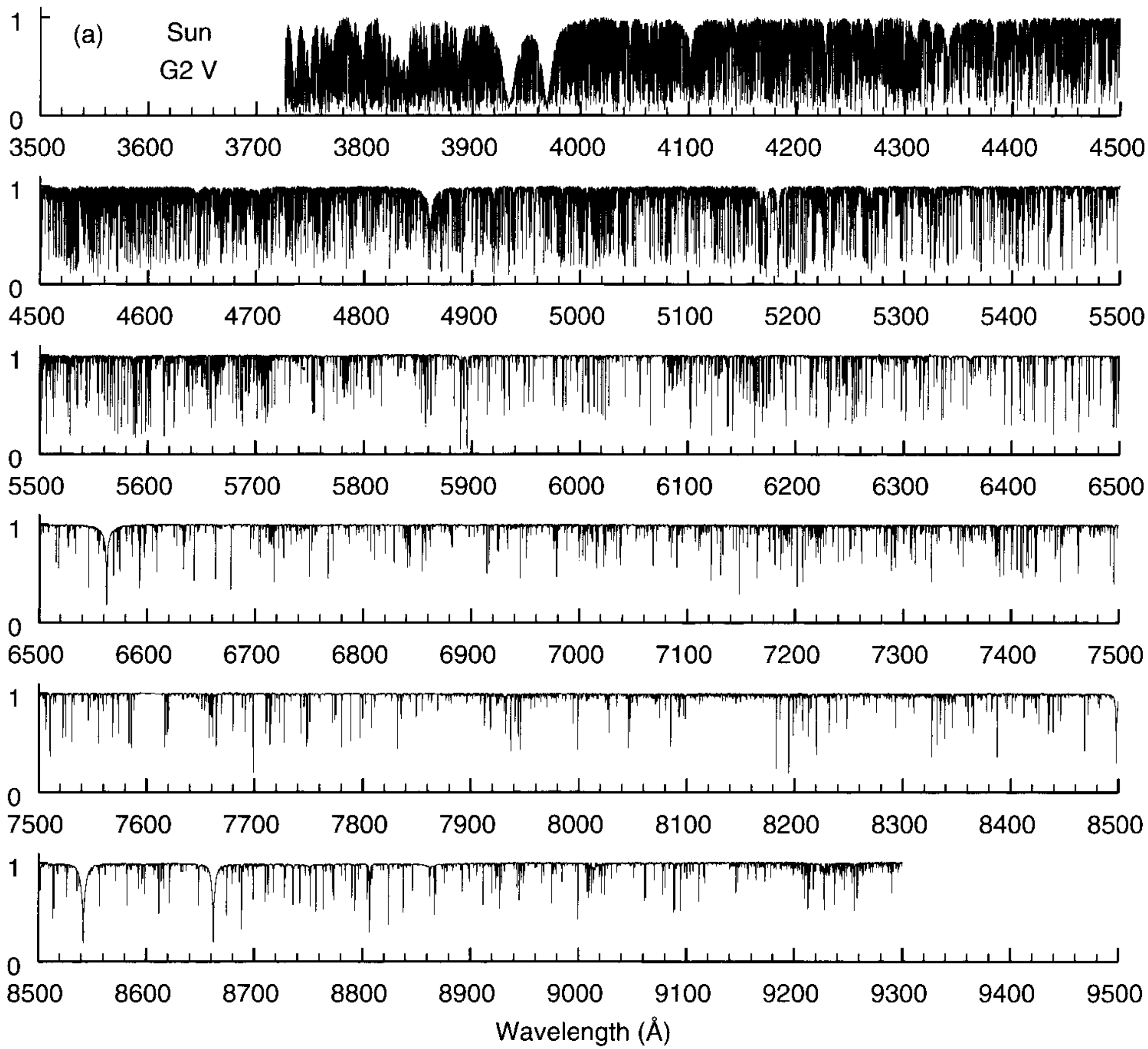
Asplund et al. (2009)

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 (Section 3.9)

log ε values

Z	Element	Photosphere	Meteorites	Z	Element	Photosphere	Meteorites
1	H	12.00	8.22 ± 0.04	44	Ru	1.75 ± 0.08	1.76 ± 0.03
2	He	[10.93 ± 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 ± 0.10]	−1.12	53	I		1.55 ± 0.08
11	Na	6.24 ± 0.04	6.27 ± 0.02	54	Xe	[2.24 ± 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

Line spectra



Absorption in stellar spectra
→ "equivalent widths"

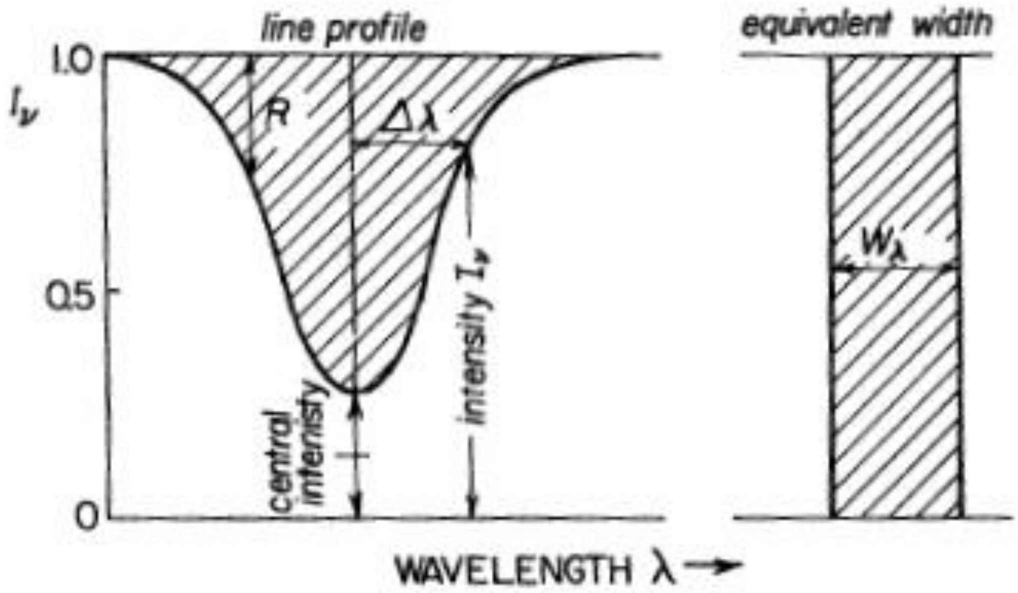


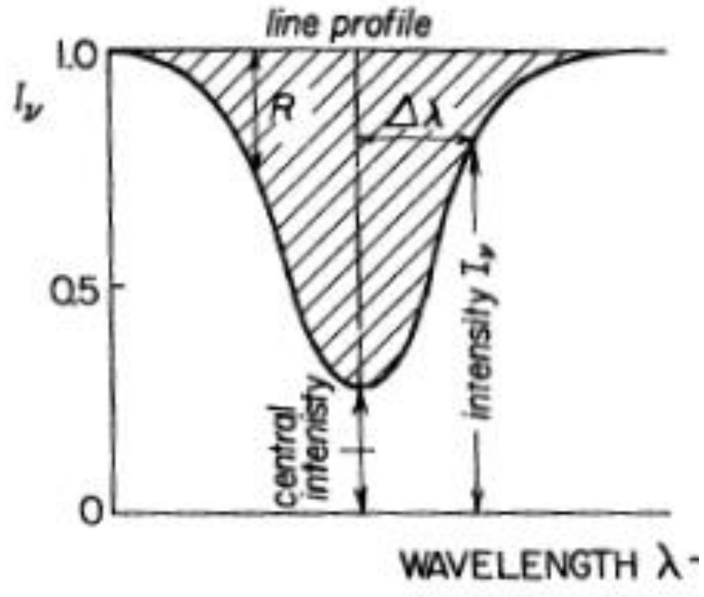
Fig. 3.4. Definition of equivalent width.

Pagel 1997

Equivalent width dose not change by broadening of stellar rotation and of instrument's resolution.

Measurements of equivalent widths

- Gaussian fitting
- Fitting of Vogt profile
- Direct integration



Measurement errors

- S/N, continuum estimate
- Fitting error
- contamination

Abundances and line strengths

"curve of growth"

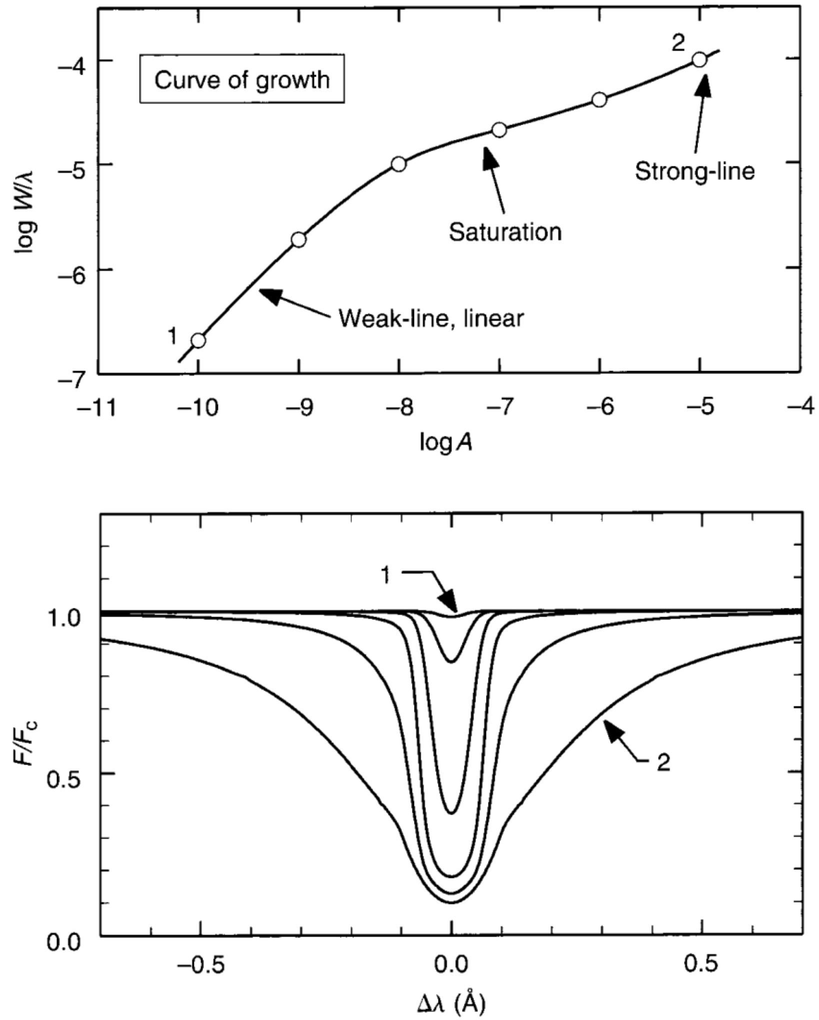


Fig. 13.11. Both the equivalent width (top) and the profile (bottom) change with chemical abundance of the absorbing species. The dots on the curve of growth correspond to the profiles below. Models have $S_0 = 0.87$ and $\log g = 4.0\,\mathrm{cm/s^2}$.

Gray 2005
The Observation and Analysis of Stellar Photospheres

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.)

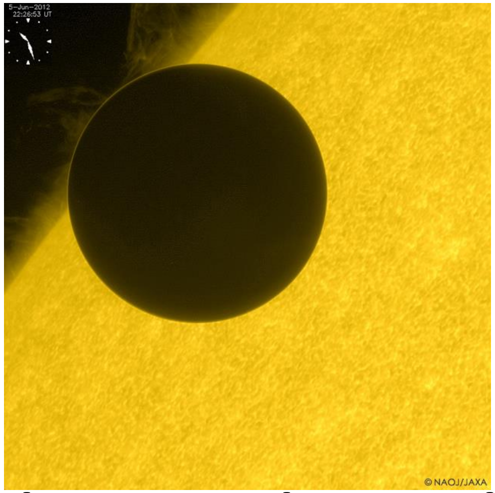
× insensitive to abundances

→low accuracy in abundance determination

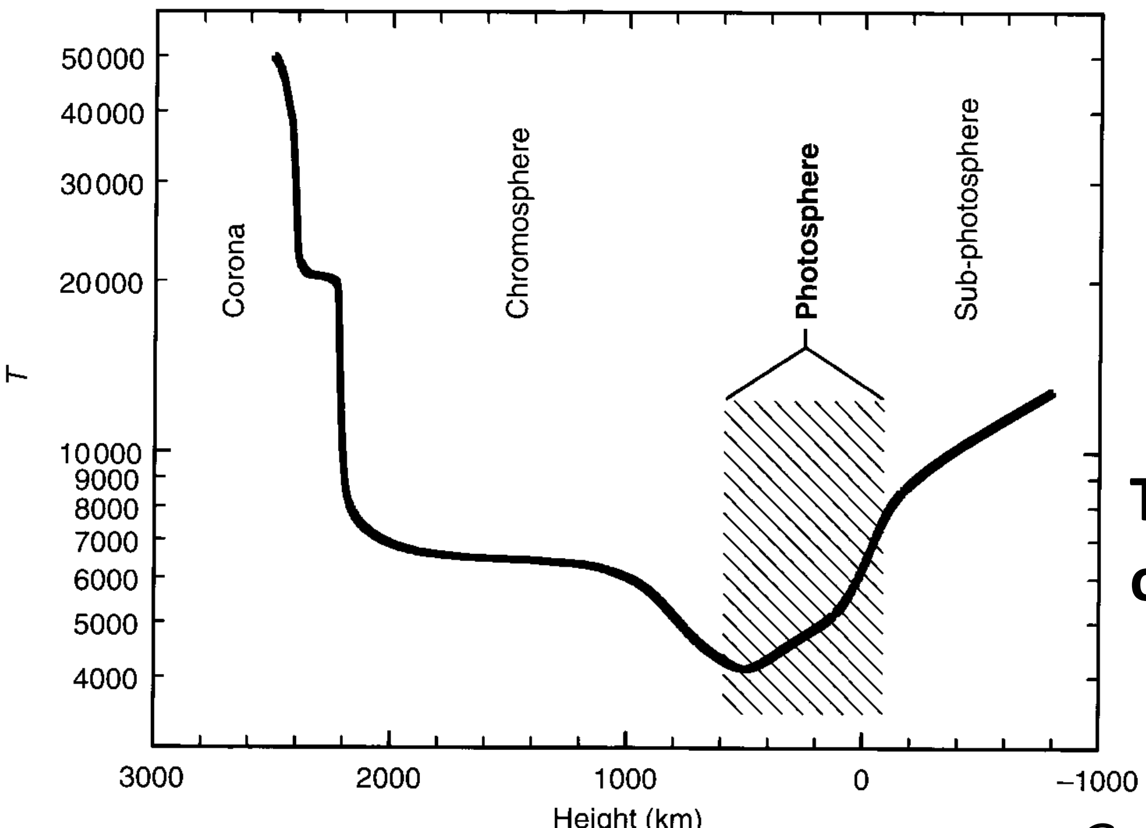
dependent on treatment of line broadening

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

Stellar atmosphere and its modeling



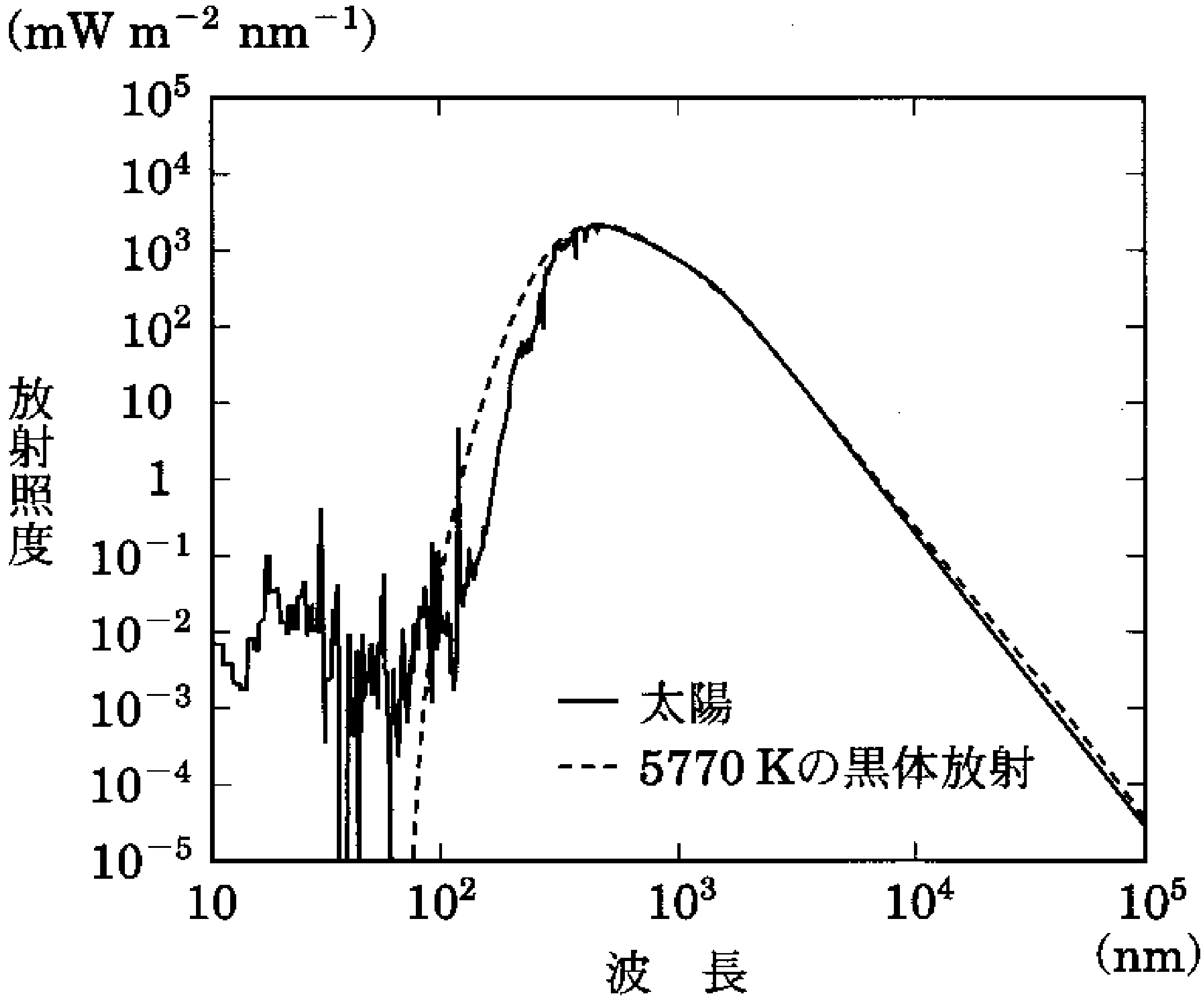
Solar atmosphere with Venus (Hinode)



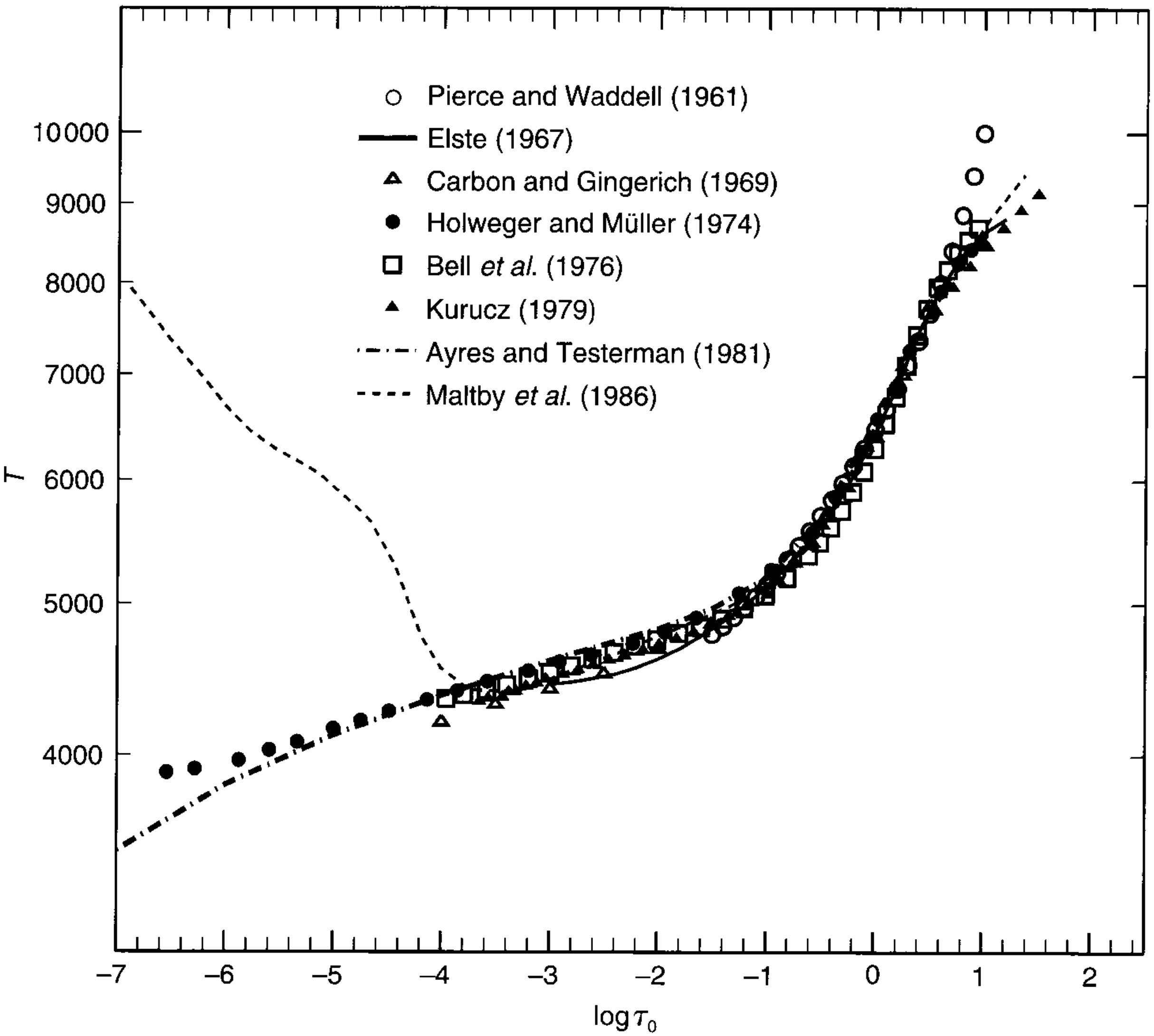
Temperature structure of the solar atmosphere

Gray 2005

Stellar atmosphere and spectra



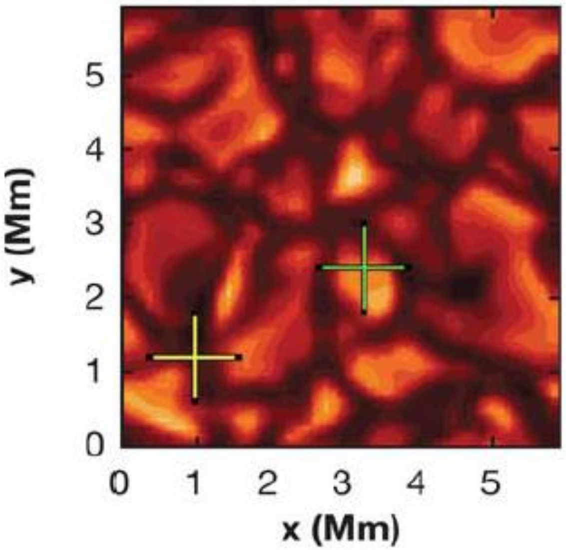
Modeling the solar photosphere

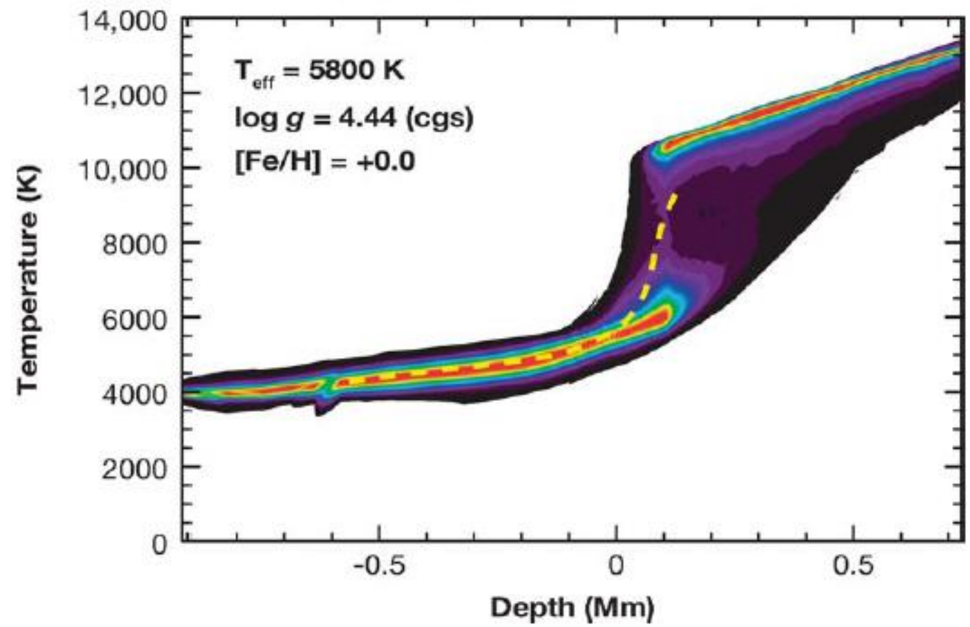


Gray 2005

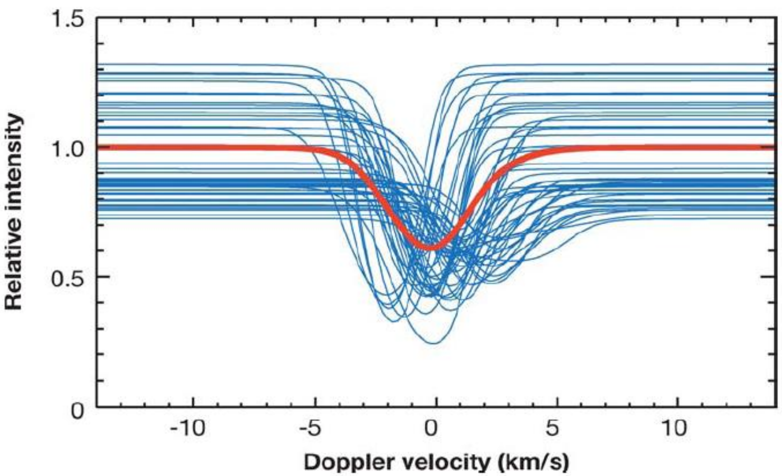
3D hydrodynamical models

Asplund (2005)





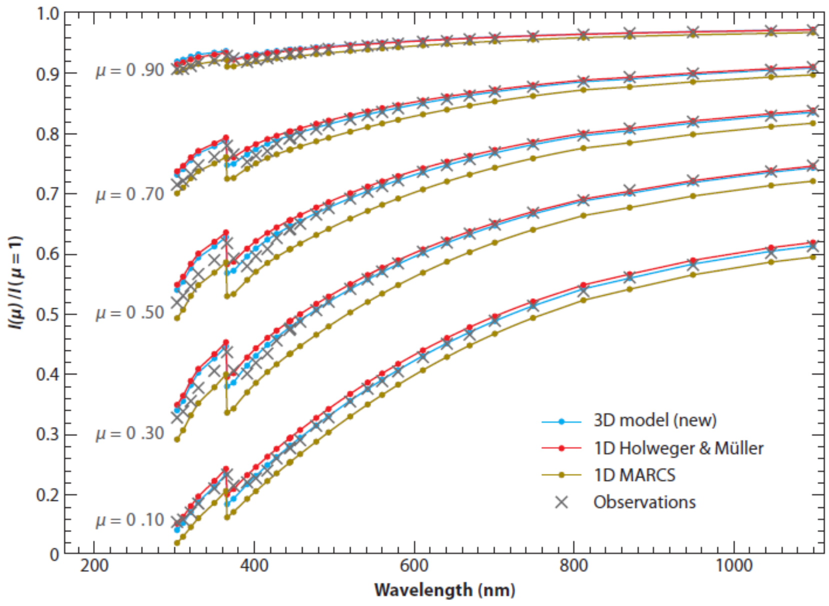
ïgure 1 Distribution of temperature with height in a 3D hydrodynamical model atmosphere ›rresponding to the Sun (Asplund et al. 2000b) with *warm colors* denoting an abundance f gas and *cold colors* a shortage of gas at those temperatures. Note the shortage of gas with temperature between 6000 and 10,000 K owing to the very rapid cooling in upflowing ıaterial as it starts to become optically thin. The zero-point in height corresponds to average ›ntinuum optical depth unity. Also shown is the temperature structure of a 1D hydrostatic ıeoretical MARCS model (Asplund et al. 1997) with otherwise identical input parameters *lashed line*), which illustrates that in the 3D model the gas is close to radiative equilibrium ı the optically thin layers at solar metallicity.



Observational evidence for the 3D effects for the solar model

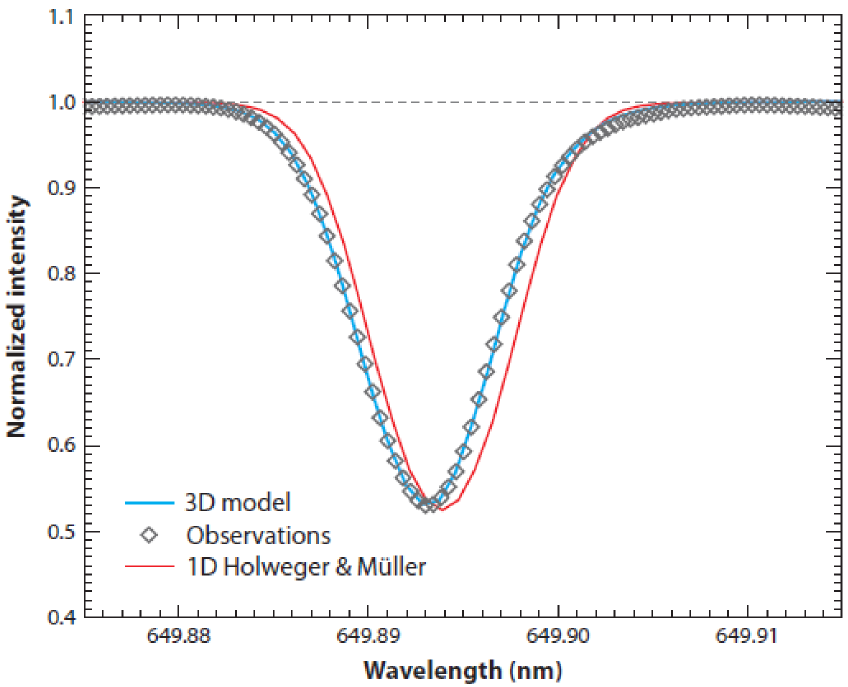
Asplund et al. (2009)

Wavelength dependence of limb darkening



wavelength

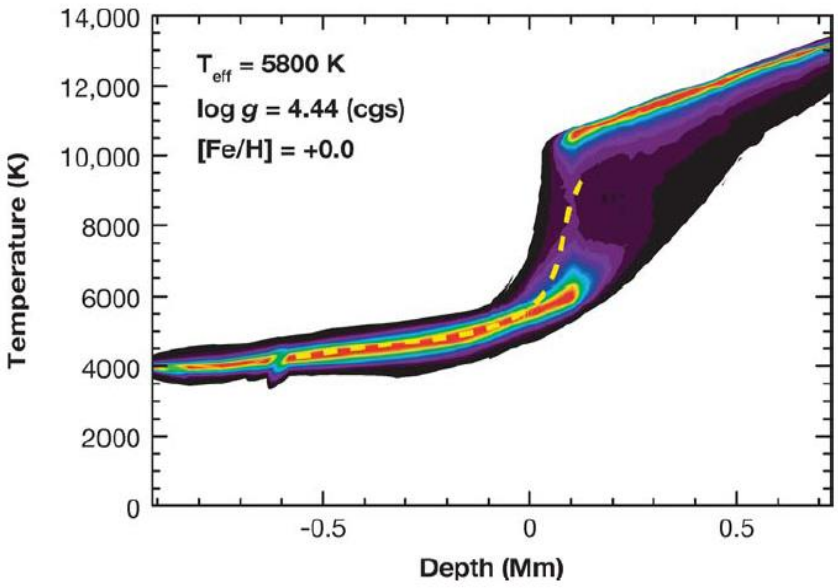
Line profile and wavelength shift



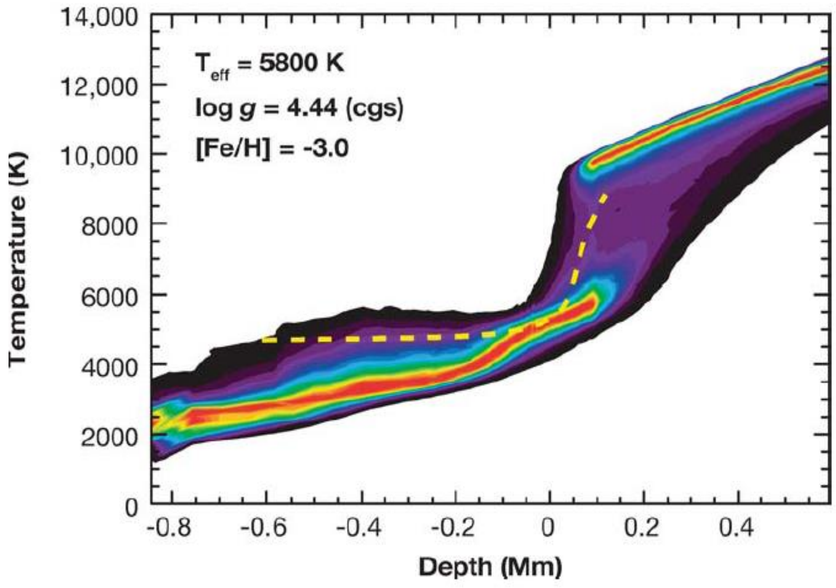
3D models for metal-poor stars

Effect is large at the surface of metal-poor stars

Solar model



Metal-poor case



Abundance analysis using model photospheres

- **Input data**
  - **model photosphere** (← stellar parameters)
  - **chemical composition** assumed
  - **line data**
    (wavelength λ, excitation potential χ, transition probability *gf*)

↓

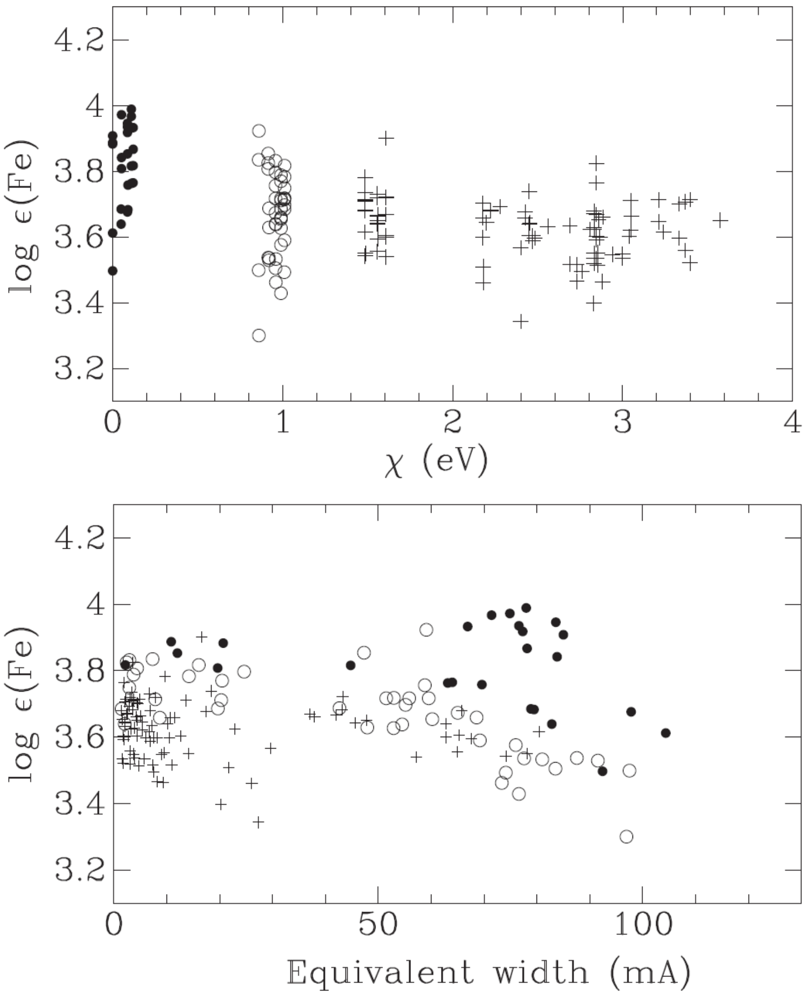
Line opacity / radiative transfer

- **output** → **comparison with observational data**
  spectrum / equivalent widths

Feedback to model parameters and chemical composition given as input data if required

Abundance determination

Analysis of equivalent widths



Aoki (2015)

Spectrum synthesis

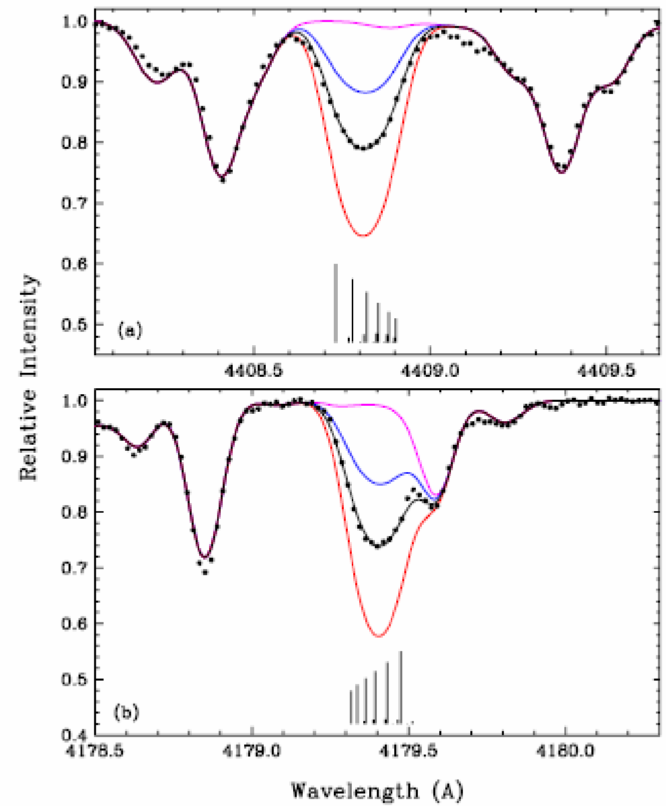


Figure 3. Observed and synthetic spectra in CS 31082−001 of two strong Pr II lines with wide hfs. In each panel, the points represent the observed spectrum. The magenta line is the spectrum computed with no contribution from Pr II; the black line is the best-fitting synthesis (with the Pr abundance given in Table 6); and the red and blue lines are the syntheses computed with Pr abundances altered by ±0.3 dex from the best value. The vertical lines have been drawn at the bottom of each panel to indicate the wavelengths and *relative* strengths (arbitrary overall normalization) of the hyperfine components that comprise the Pr II transitions.

Sneden et al. (2009)

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 line 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])

Errors in abundance analyses

- **Uncertain case:**
  - -derived only from strong absorption features
  - -derived from species in minor ionization stage
    - ex. Fe abundances from neutral Fe in solar photosphere
  - -derived from high excitation lines (minor population)

- **Robust case:**
  - -abundance ratios of two elements derived from the same ionization stage.
    - e.g. Mg/Fe from neutral Mg and 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)

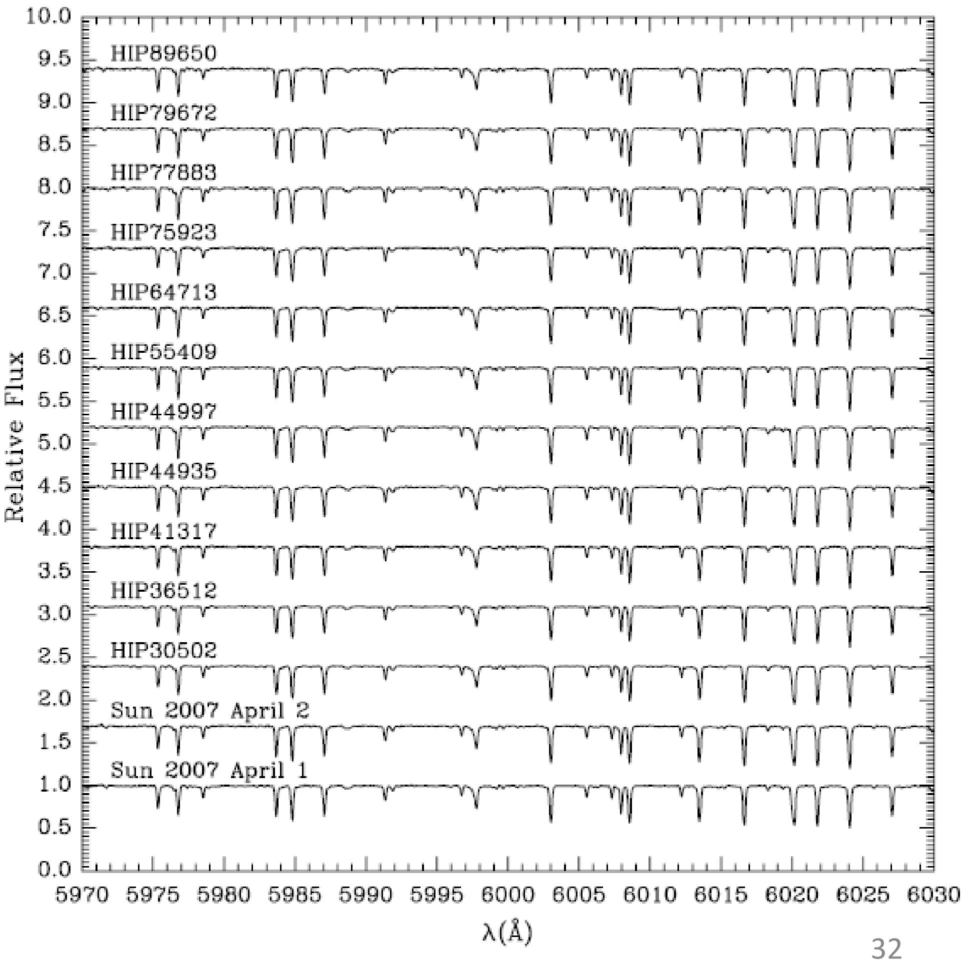
Observations and Analysis (1)

- Targets:

  -11 solar twins (no planet information)

  -10 solar analogs (with and without giant planets)
- Planets are not well searched for solar twins, while the solar analogs are selected from planet survey.
- 6.5m Magellan telescope and MIKE (E=65,000)

  + Keck/HIRES for one object



Differential analysis for "solar twin" stars

Melendez et al. (2009)

Observations and Analysis (2)

•A "model independent analysis": direct comparison of line EWs between Sun and a star for different excitation potential and elements.

•Analysis with models are also made.

•Parameters:

-Effective temperatures (T_{eff}) from excitation equilibrium

-Surface gravity (log g): ionization equilibrium of Fe I/Fe II

Solar twins have T_{eff} within 75K, log g within 0.10dex and [Fe/H] within 0.07dex.

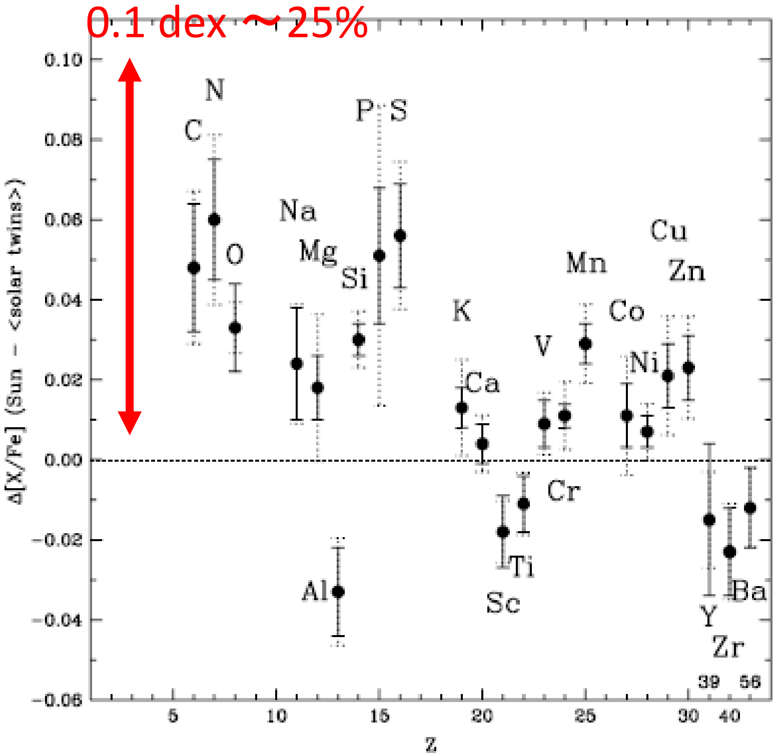
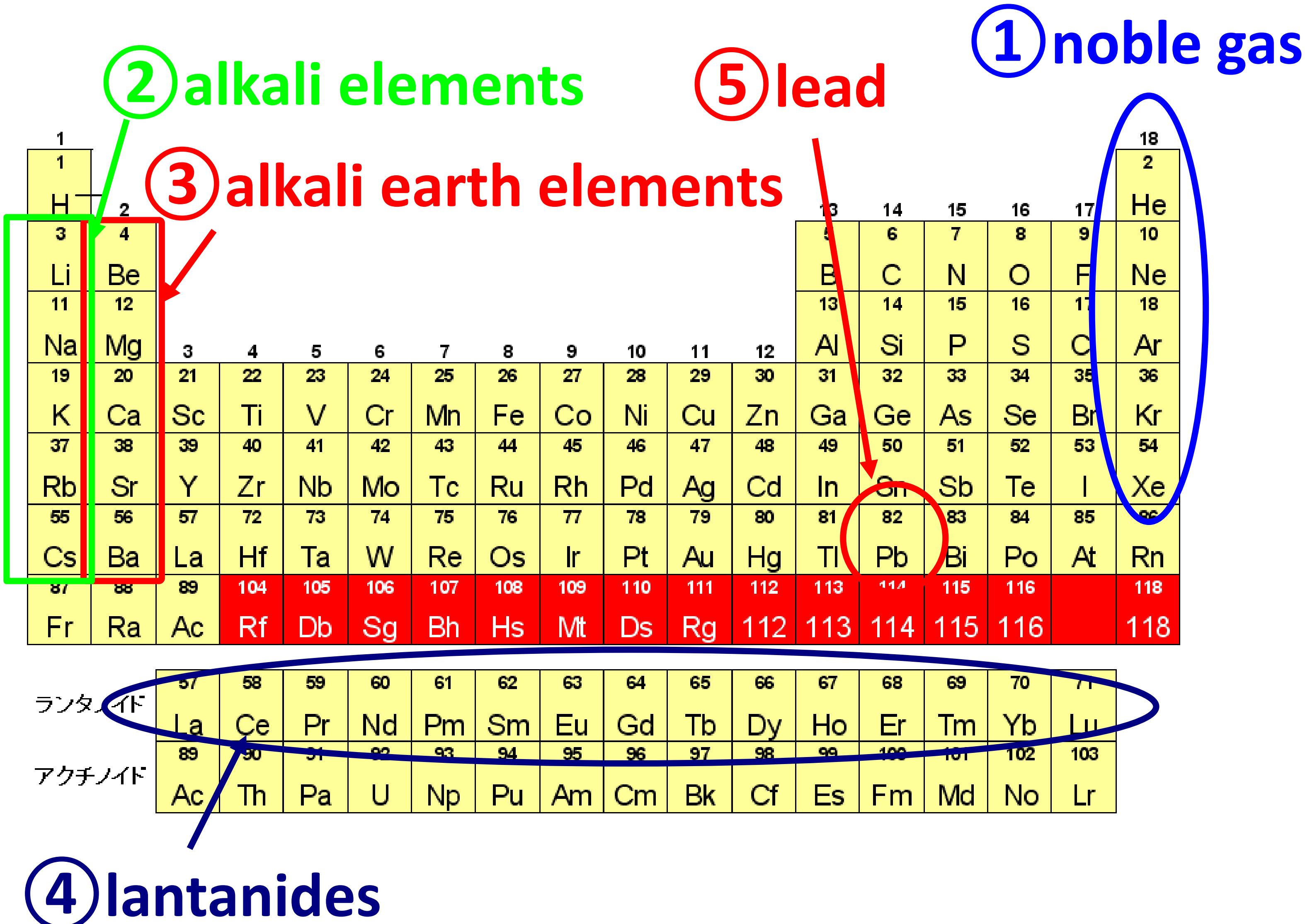


Figure 2. Differences between [X/Fe] of the Sun and the mean values in the solar twins as a function of atomic number Z. For clarity, the elements Y ($Z = 39$), Zr ($Z = 40$), and Ba ($Z = 56$) have been included after Zn. Observational 1σ errors in the relative abundances (including observational errors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

Chemical property and abundance measurements

Which elements can be measured?



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 neutral 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.

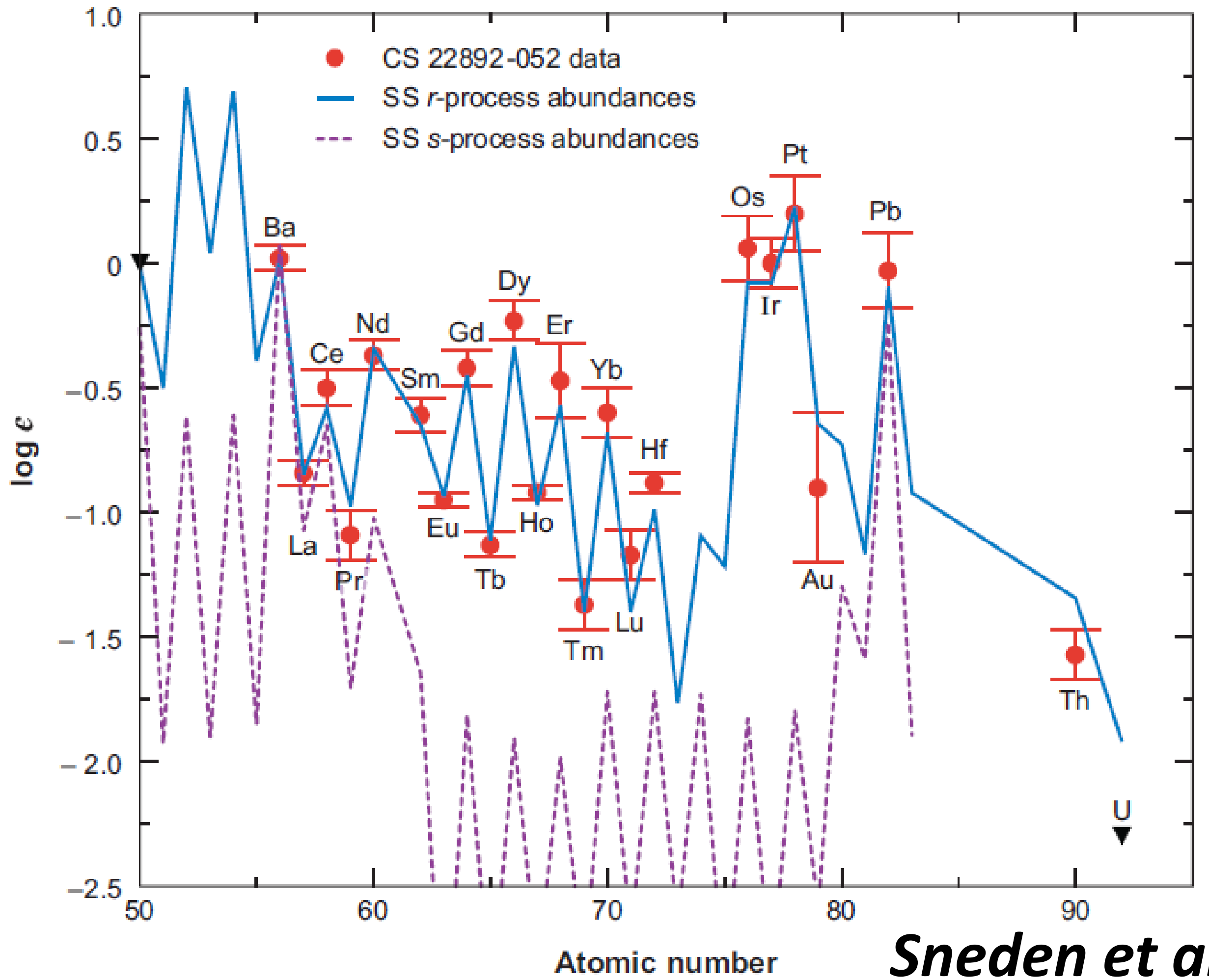
④lantanides:La, Ce, Pr, Nd, Sm, Eu, Gd, Dy, ...

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

⑤lead

Measurable lines exist in the optical range.

Lantanides abundances determined for "r-process-enhanced" very metal-poor stars



Sneden et al. (2008)

Update 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)
....

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

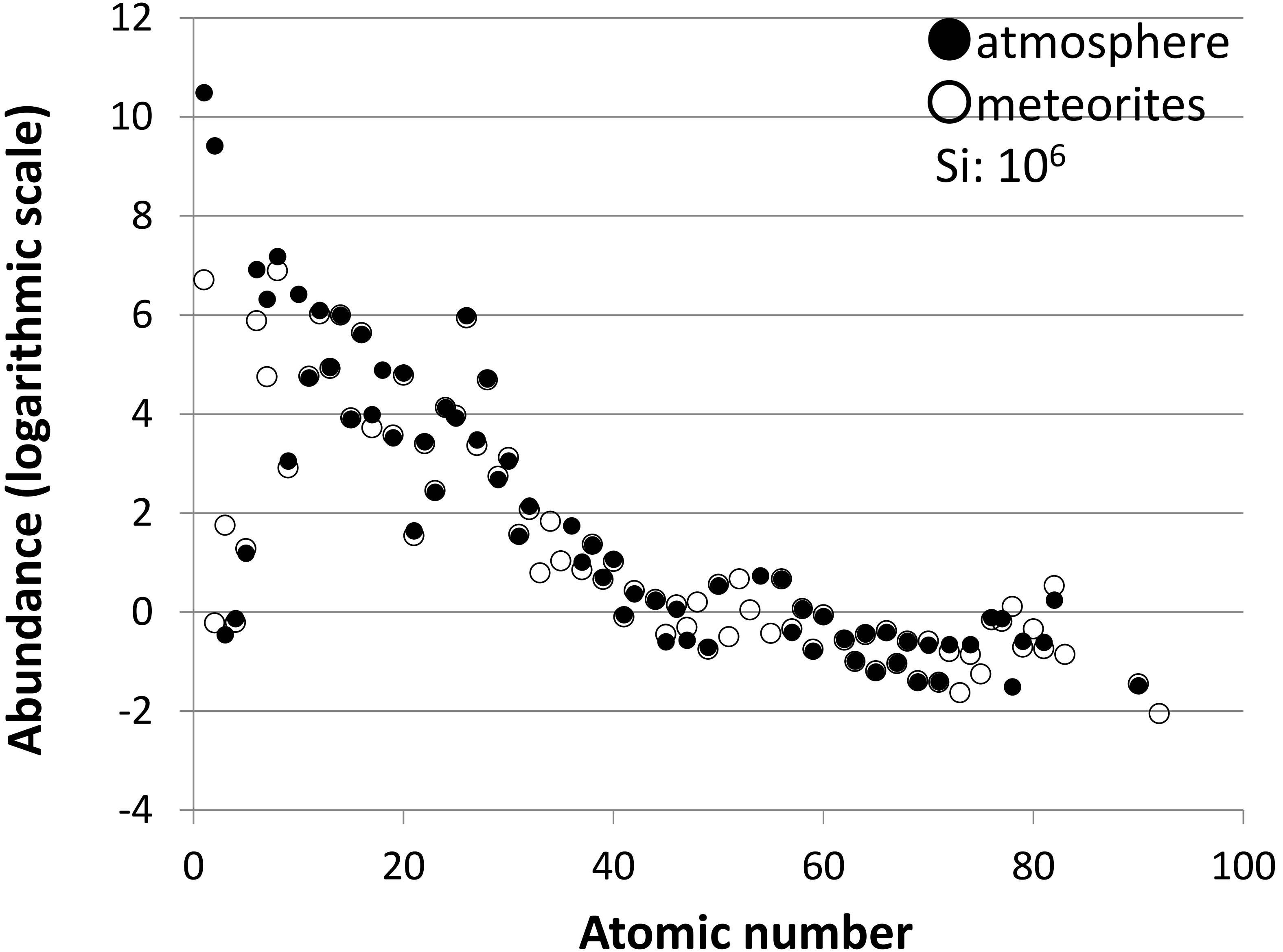
- Abundance ratios are robust in general.
  e.g. Eu/Fe, La/Eu

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

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, …

Solar chemical composition



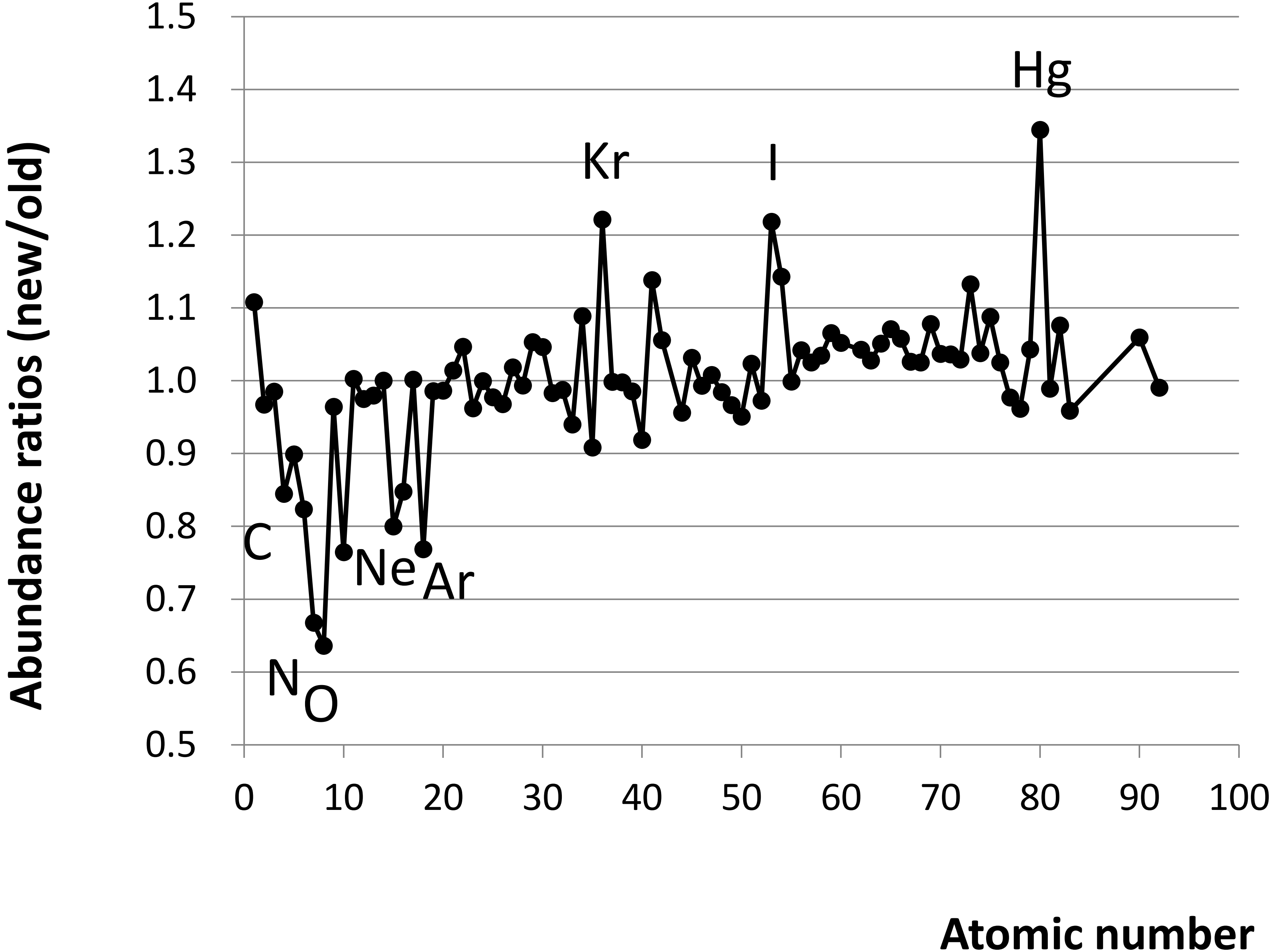
Analysis and compilation of solar abundances

- **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「宇宙の組成」

Solar chemical composition



Isotope ratios

- Isotopes: having same number of protons but different number of neutrons
  →same(similar) chemical property, but different mass

- Spectral lines of isotopes are similar, but wavelengths are slightly different
  -difference of nuclear mass
  -difference of nuclear spin

Nuclear chart

16											S 26 0.012s	S 27 0.021s	S 28 0.125s	S 29 0.187s	S 30 1.178s
15											P 25 0.0368s	P 26 0.0437s	P 27 0.26s	P 28 0.2703s	P 29 4.142s
14									Si 22 0.029s	Si 23 0.0423s	Si 24 0.14s	Si 25 0.22s	Si 26 2.234s	Si 27 4.16s	Si 28 92.2297
13									Al 21 0.0428s	Al 22 0.0911s	Al 23 0.446s	Al 24 2.053s	Al 25 7.183s	Al 26 7.17e+05y	Al 27 100
12								Mg 19 4e-12s	Mg 20 0.0908s	Mg 21 0.122s	Mg 22 3.875s	Mg 23 11.32s	Mg 24 78.99	Mg 25 10	Mg 26 11.01
11								Na 18 0.0347s	Na 19 0.435s	Na 20 0.4479s	Na 21 22.49s	Na 22 2.603y	Na 23 100	Na 24 15h	Na 25 59.1s
10							Ne 16	Ne 17 0.1092s	Ne 18 1.666s	Ne 19 17.22s	Ne 20 90.48	Ne 21 0.27	Ne 22 9.25	Ne 23 37.24s	Ne 24 3.38m
9							F 15 0.14s	F 16 1e-19s	F 17 1.075m	F 18 1.83h	F 19 100	F 20 11.16s	F 21 4.158s	F 22 4.23s	F 23 2.23s
8					O 12	O 13 0.00858s	O 14 1.177m	O 15 2.037m	O 16 99.757	O 17 0.038	O 18 0.205	O 19 26.88s	O 20 13.51s	O 21 3.42s	O 22 2.25s
7					N 11 0.09s	N 12 0.011s	N 13 9.965m	N 14 99.632	N 15 0.368	N 16 7.13s	N 17 4.173s	N 18 0.619s	N 19 0.271s	N 20 0.13s	N 21 0.095s
6			C 8	C 9 0.1265s	C 10 19.31s	C 11 20.39m	C 12 98.93	C 13 1.07	C 14 5700y	C 15 2.449s	C 16 0.747s	C 17 0.193s	C 18 0.092s	C 19 0.049s	C 20 0.014s
5				B 8 0.77s	B 9 8.5e-19s	B 10 19.9	B 11 80.1	B 12 0.0202s	B 13 0.01736s	B 14 0.0125s	B 15 0.0105s		B 17 0.00508s		B 19 0.00292s
4				Be 7 53.22d	Be 8 6.7e-17s	Be 9 100	Be 10 1.51e+06y	Be 11 13.81s	Be 12 0.0213s		Be 14 0.00484s				
3				Li 6 7.59	Li 7 92.41	Li 8 0.8399s	Li 9 0.1783s		Li 11 0.0087s						
2		He 3 0.000137	He 4 99.9999		He 6 0.8067s		He 8 0.1191s								
1	H 1 99.9885	H 2 0.0115	H 3 12.32y												
0		n 1 10.23m													

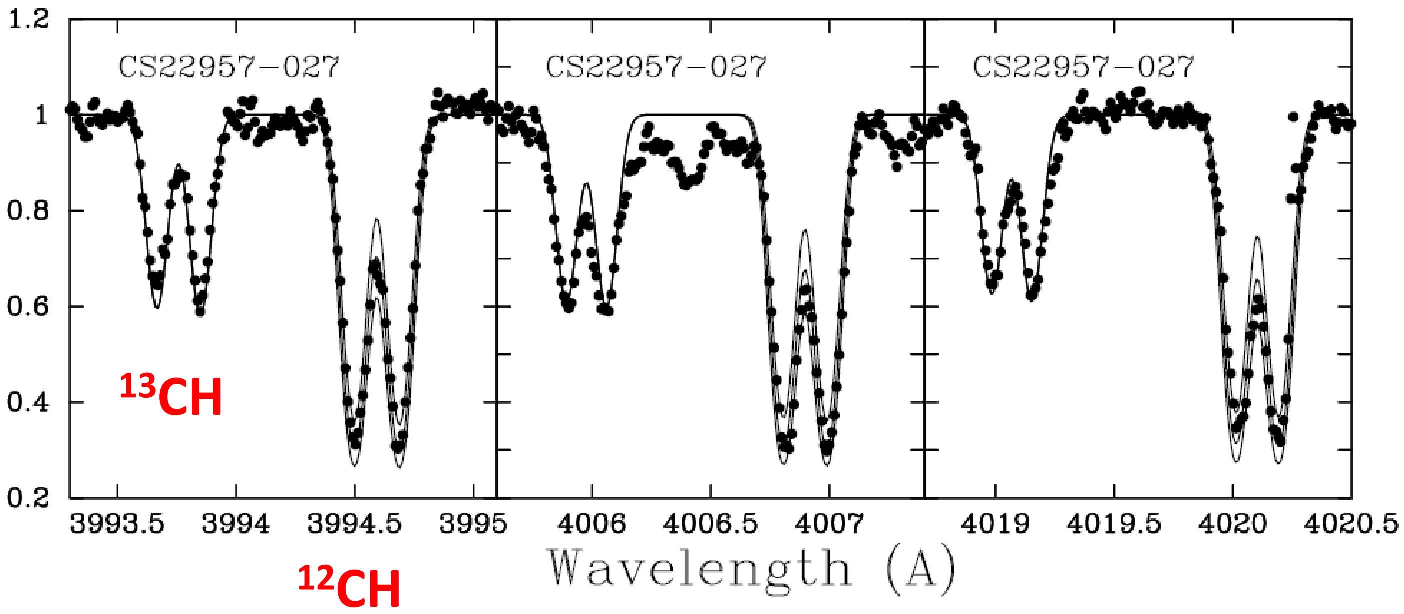
Proton number→

Neutron number→

Measurement of isotopes: molecular lines

Large effect of mass difference on molecular spectra

CH molecules



Aoki et al. (2002)

Mg isotopes

MgH molecular lines

$^{24}Mg/^{25}Mg/^{26}Mg$

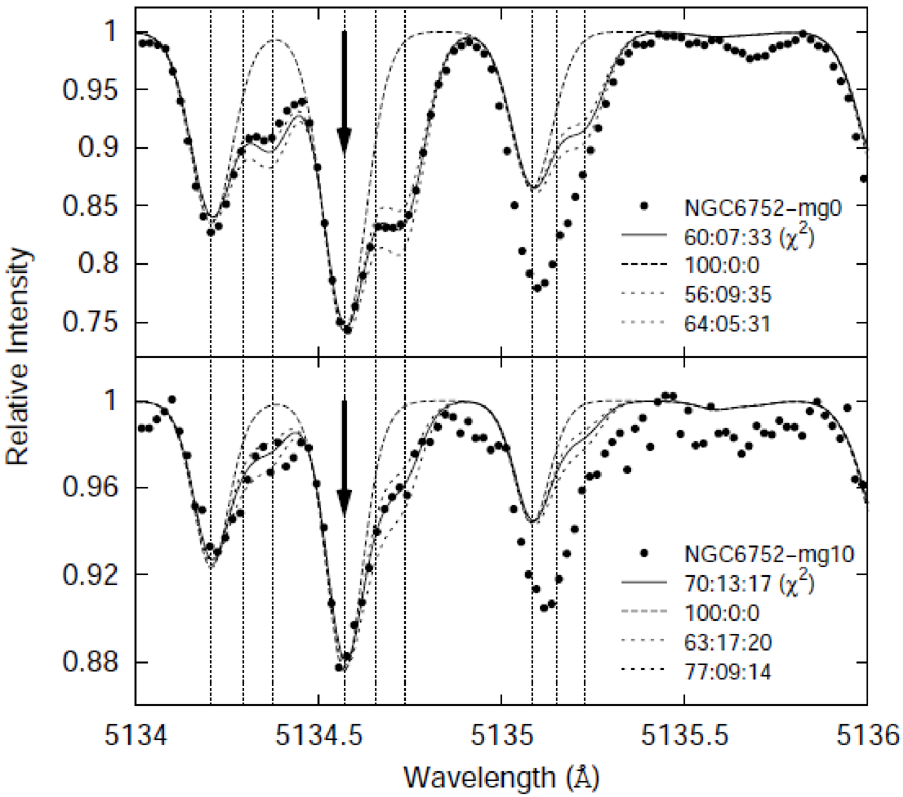
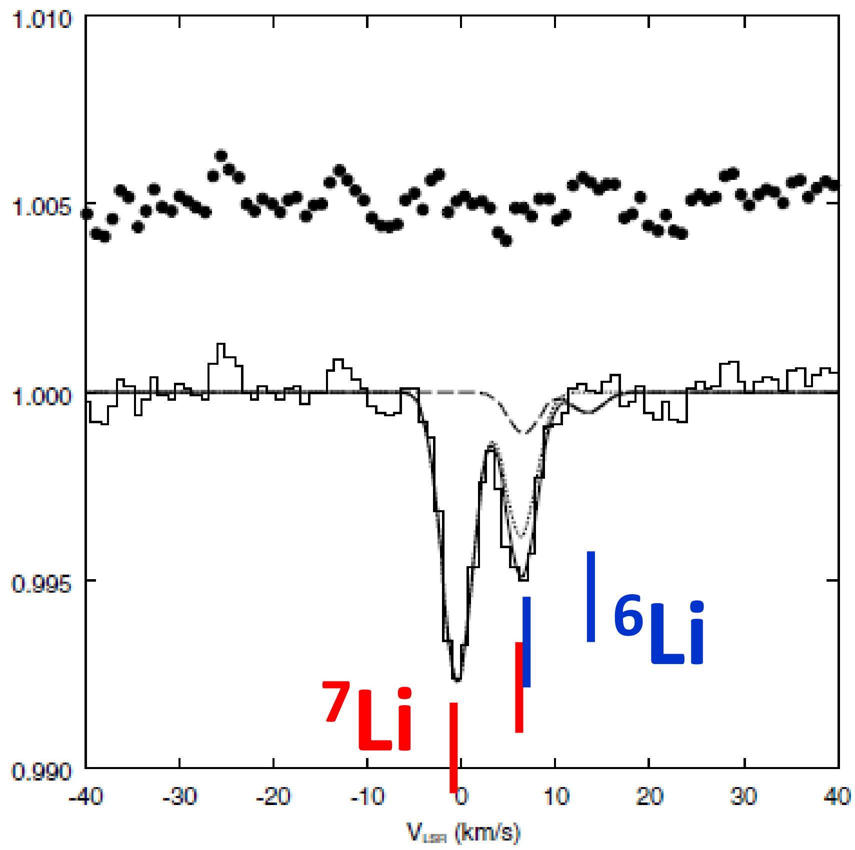


Fig. 7. Spectra of NGC 6752-mg0 (upper) and NGC 6752-mg10 (lower) from 5134.0 to 5136.0 Å. The feature we are interested in fitting is highlighted by the arrow. The positions of the ^{24}MgH, ^{25}MgH, and ^{26}MgH lines are indicated by dashed lines. The closed circles represent the observed spectra. The synthetic spectrum generated using the isotopic ratios determined by χ^2 analysis is given by the solid line: the ^{24}Mg:^{25}Mg:^{26}Mg ratios are given on the figure. Unsatisfactory ratios are plotted as dotted lines.

Yong et al. (2003)

Li isotopes in interstellar matter



Kawanomoto et al. (2009)

Measurement of isotopes: light elements

^{6}Li measurements for a metal-poor star (1993)

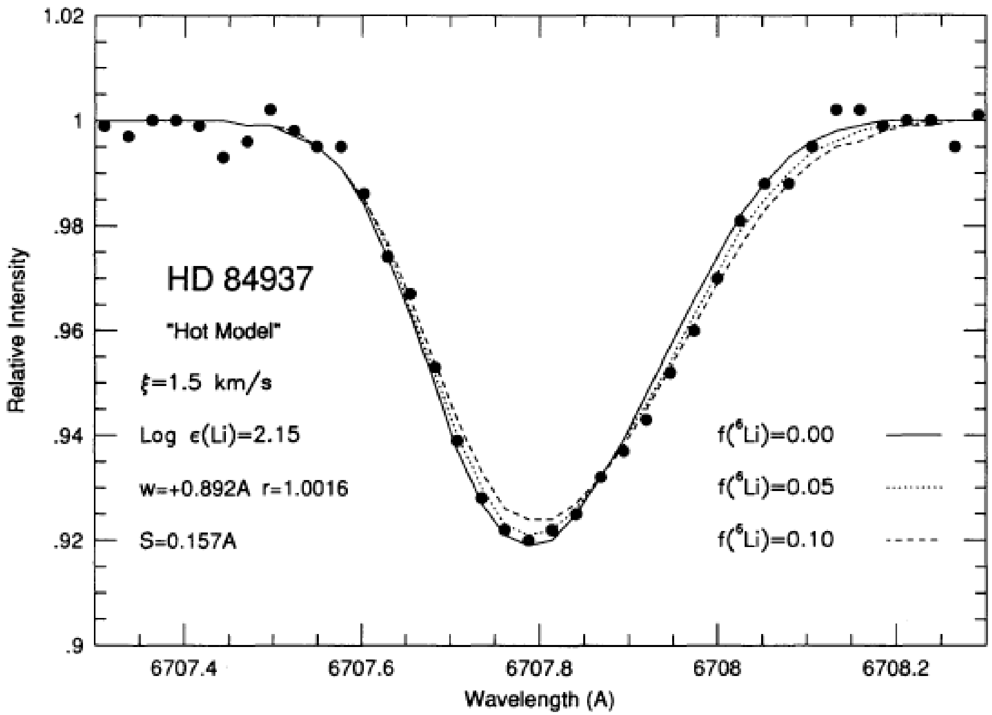


FIG. 13.—Li I line-profile HD 84937 (filled circles are the observed points) with three synthetic spectra (*continuous curves*) generated from a hotter (T_{eff} = 6135 K) model atmosphere. Compared to the best model atmosphere, the Li abundance is increased by +0.03 dex and the smoothing (derived from the Ca I 6162.17 Å line) is increased by +0.004 Å, however, the best estimate for $f(^6Li)$ is not changed significantly using this hotter model atmosphere.

Smith et al. (1993)

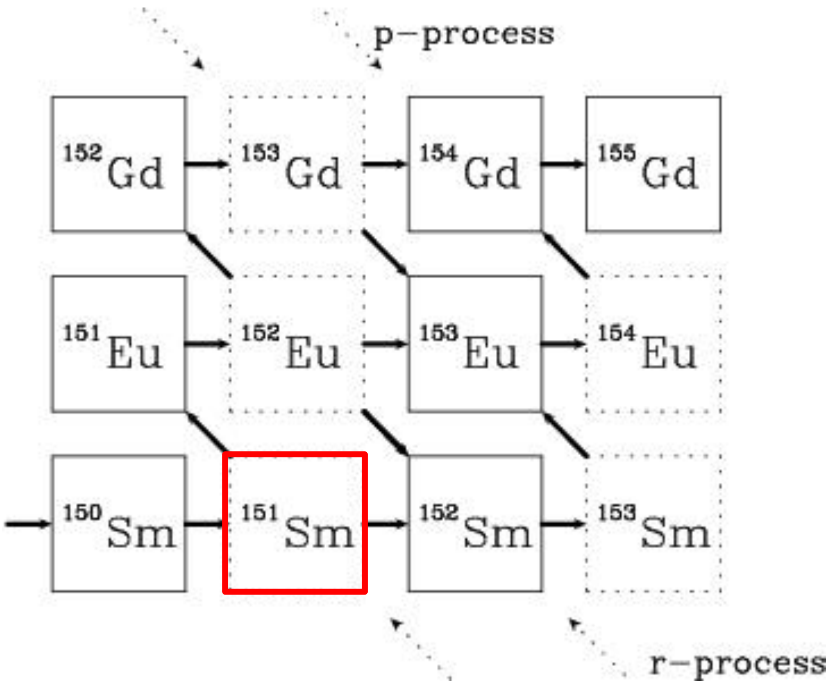
Measurement of isotopes: hyperfine splitting of spectral lines of heavy elements

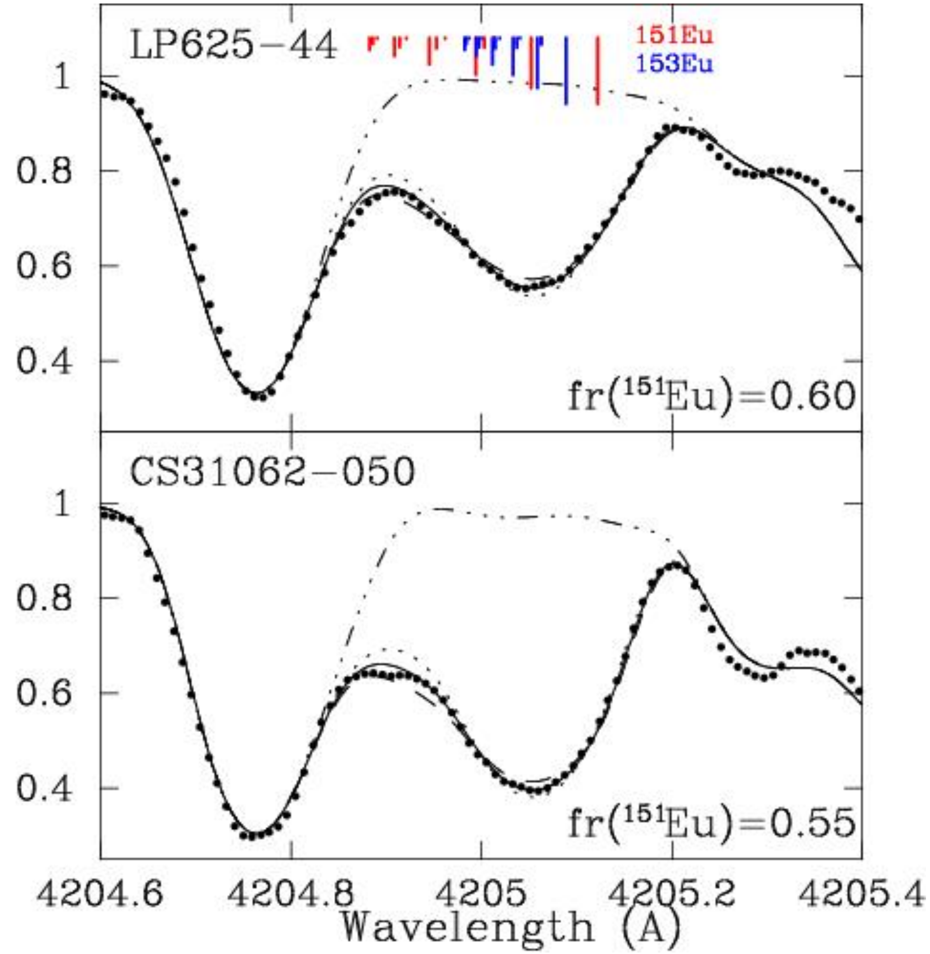
Large effect of hyper fine splitting on spectral lines of heavy elements that depends on isotopes

- **Splitting of spectral lines due to difference of nuclear spin**
- **Large effect on odd nuclei**

Isotope abundances

Eu isotopes ～ easiest case?



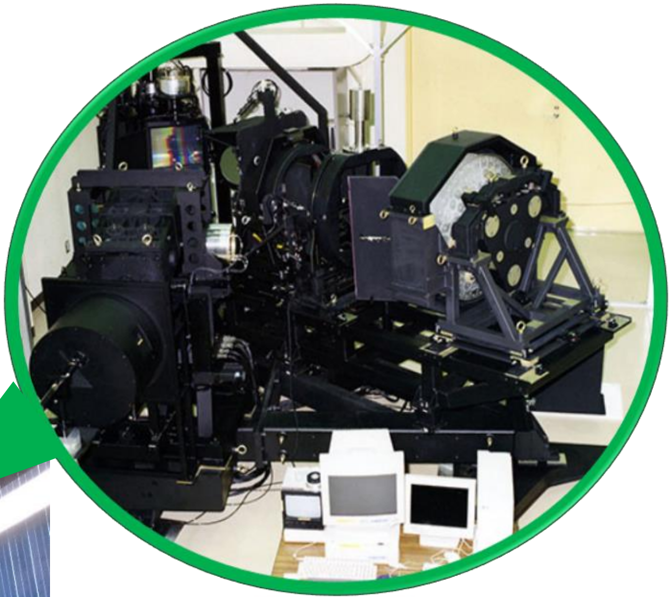


Aoki et al. (2003)

Facilities for measurements of stellar chemical composition

High-resolution spectrometer mounted on large telescope

- **High-resolution spectroscopy is essential to determine accurate stellar chemical composition.**
- **Large light collecting power provided by large telescope is necessary for high-resolution spectroscopy.**



Hgh Dispersion Spectrograph (HDS)

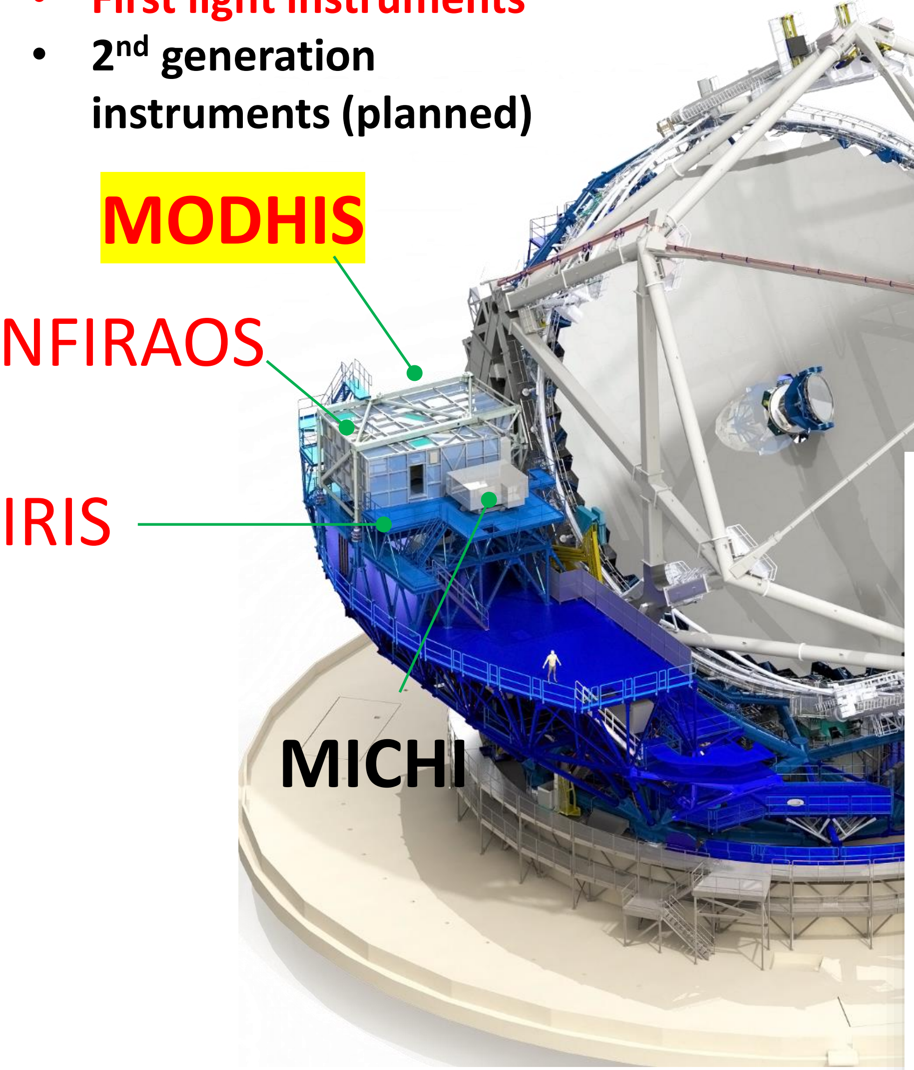
Subaru Telescope

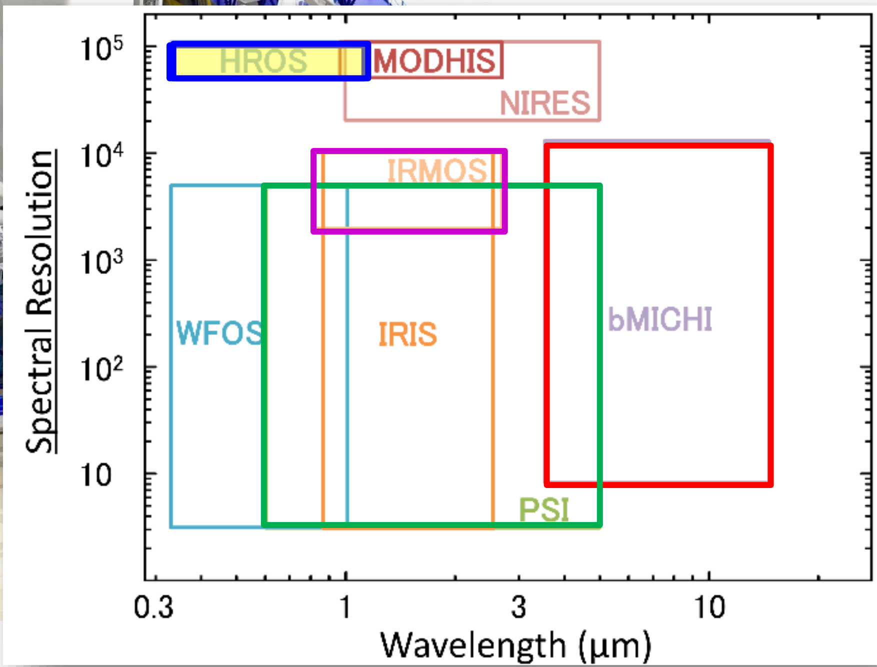
Extremely Large Telescope TMT

TMT = Thirty Meter Telescope

TMT science instruments

- **First light instruments**
- **2nd generation instruments (planned)**





Stellar chemical compositions to constrain nucleosynthesis in the universe: Summary

What can we know from chemical abundances of stellar surface?

⇒Chemical abundances of cool stars are useful record of the chemical composition of the universe at the time the stars formed, while they are partially modified during stellar evolution (depending on elements).

How are chemical abundances determined from stellar spectra?

⇒Standard analysis method using model stellar atmosphere is established. Reliable models and atomic/molecular spectral line data are required.

Which elements can we measure the abundances? How accurately can we measure?

⇒Alkaline earth elements (Mg, Ca, Sr, etc.) and lanthanides are measurable in most cool stars, while noble gases (He, Ne, etc.) are not accessible. Abundance ratios of metals (e.g., Mg/Fe, Sr/Ba) are better determined than absolute ones (e.g, log ε(Fe)). Relative abundances between similar type stars are robust.