The chemical evolution of Sr and its neighbouring elements

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Outline - The chemical evolution of strontium

- Telescopes and instruments
- Stellar abundances
- Sr - assumptions and corrections
- Formation processes and chemical evolution

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Very Large Telescope (VLT) - 8-m mirror

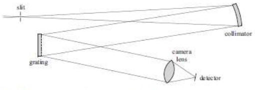
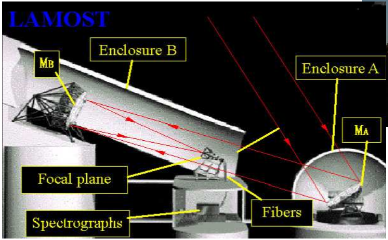
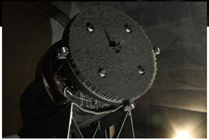


Fig. 1.— The essential components of an astronomical spectrograph.

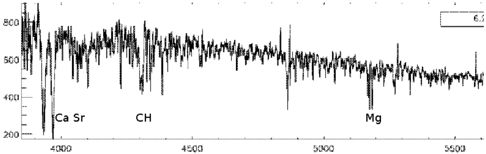
Simple sketch of a spectrograph – Massey et al.

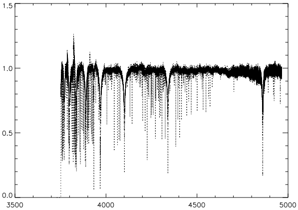
Large Sky Area Multi-Object Fiber Spectroscopic Telescope (LAMOST) — 4-m mirror, 4000 fibres $\rightarrow 10000$ stars/night or $2 \cdot 10^6$ stars/year





LAMOST vs UVES spectra

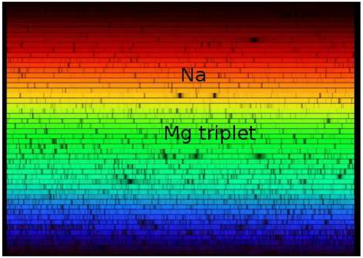


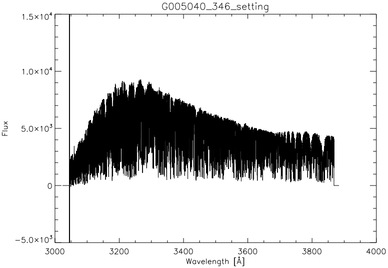


LAMOST (low resolution $R \sim 1800$) and ESO VLT (UVES - high resolution $R \sim 40000$)

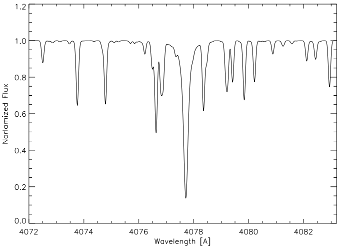
Important: Sr may be the only heavy element for which we will be able to derive abundances in low-resolution spectra.

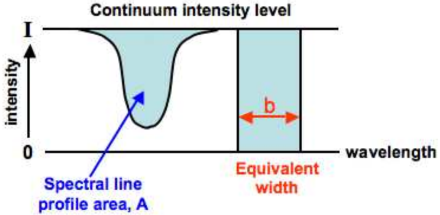
Stellar spectra – 2D to 1D



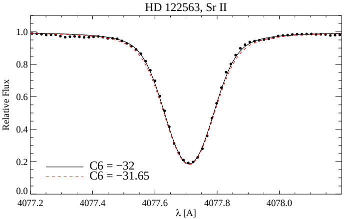


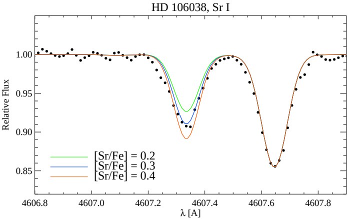
Stellar spectra and equivalent width (W)





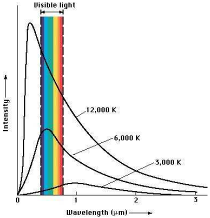
Strontium


HD 122563, Sr II
Relative Flux
λ [A]
C6 = −32
C6 = −31.65
1.0
0.8
0.6
0.4
0.2
0.0
4077.2
4077.4
4077.6
4077.8
4078.0


HD 106038, Sr I
Relative Flux
λ [A]
[Sr/Fe] = 0.2
[Sr/Fe] = 0.3
[Sr/Fe] = 0.4
1.00
0.95
0.90
0.85
4606.8
4607.0
4607.2
4607.4
4607.6
4607.8

Two ways of deriving abundances:

- Equivalent width and synthetic spectra
- We need to know the stellar parameters: Temperature, gravity, metallicity and velocity (small scale)
- Model atmosphere (e.g. MARCS) and synthetic spectrum code (e.g. MOOG)
- Assumptions: 1D, LTE – one local temperature, black body ratiation (Planck), Maxwellian velocity distribution, Boltzmann and Saha describe excitation and ionisation
- Line lists with atomic and molecular information (excitation potential and log gf)



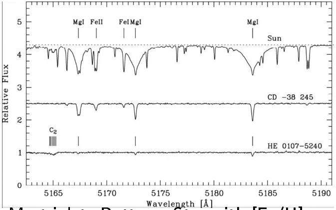
Temperature, gravity and metallicity

- The color of a star depends on two factors: Temperature and metallicity
- Color (V-K) calibration:
  $T = a + b(V-K) + c(V-K)^2 + d(V-K)[Fe/H] + ...$
- Excitation potential - based on Fe lines (3D, NLTE sensitive)
- Parallax/distance (π):
  $log\frac{g}{g_{Sun}} = log\frac{M}{M_{Sun}} + 4\frac{T}{T_{Sun}} + 0.4V_o + 2log(\pi) + corrections$
- Ionisation equilibrium from Fe lines (NLTE sensitive)
- Metallicity ([Fe/H]) from equivalent widths of Fe lines

Stellar abundances and [Fe/H]

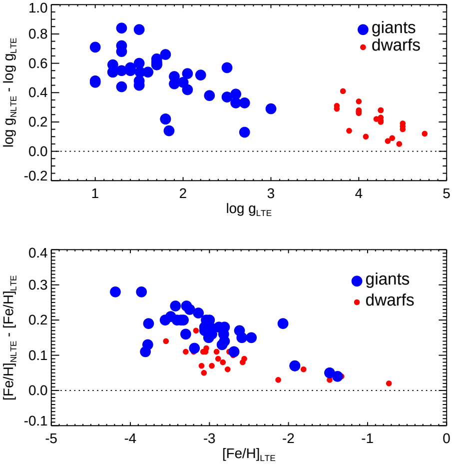
$$\log \mathrm{W} = \log(const) + \log(A) + \log(gf\lambda) - \theta\chi - \log(\kappa) \qquad (1)$$

$$[\mathrm{Fe/H}] \equiv \log(N_{\mathrm{Fe}}/N_{\mathrm{H}})_{*} - \log(N_{\mathrm{Fe}}/N_{\mathrm{H}})_{\odot} \qquad (2)$$



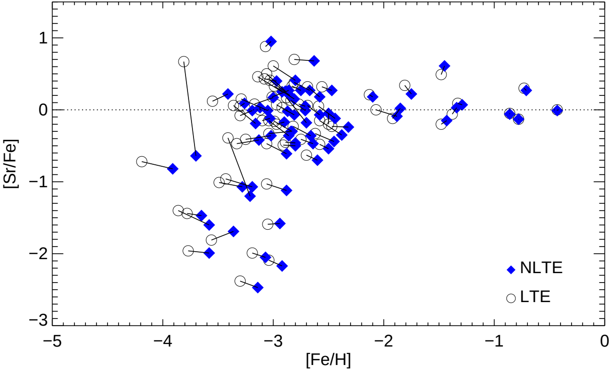
Top: Solar ([Fe/H] = 0) spectrum – Mg triplet. Bottom: Star with [Fe/H] $\sim$ -5. Christlieb +2004

Assumptions: LTE vs NLTE - the impact on stellar parameters



Hansen et al. 2013

Assumptions: LTE vs NLTE - Strontium



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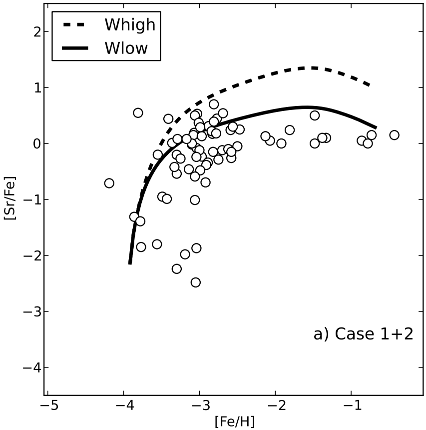
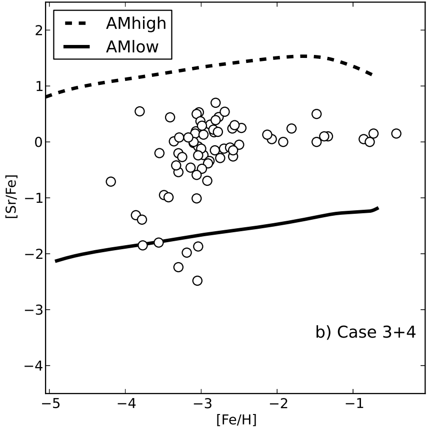
Chemical evolution of Sr from O-Mg-Ne faint CCSN

Yields from Wanajo et al.



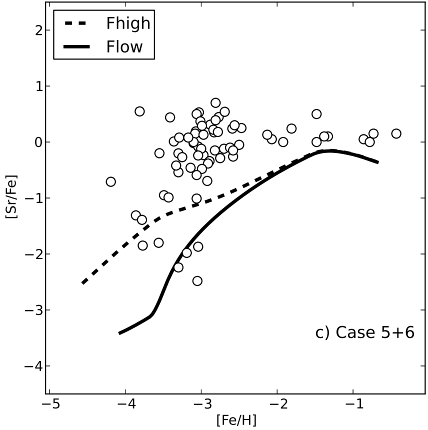
Chemical evolution of Sr from neutrino-driven winds

Yields from Arcones & Montes

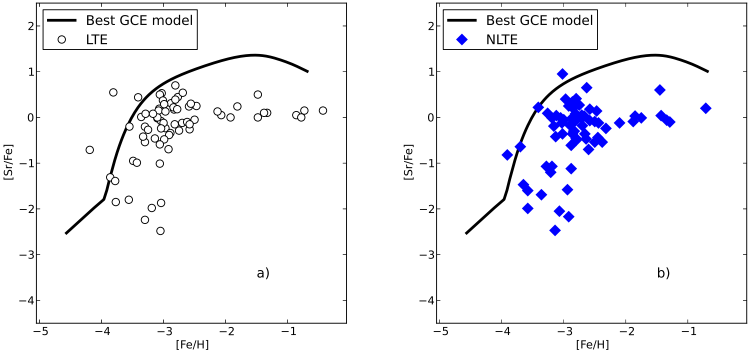


Chemical evolution of Sr from fast rotating stars

Yields from Frischknecht et al.



The chemical evolution of Sr – LTE vs NLTE Two processes are needed



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1D vs 3D

Calculations based on CO5BOLD for the 4077.7A Sr line (E. Caffau):

Line strength Sr II [mA]	Giant $3D- < 3D >$	Giant 3D - 1D	Dwarf $3D- < 3D >$	Dwarf 3D - 1D
178	0.142	0.118	-	-
158	0.198	0.151	-	-
100	-	-	0.246	0.077
85	-	-	0.278	0.092

G: 4500/2.0/-3.0/1.8, Dw: 5900/4.0/-2.0/1.5

The corrections are sensitive to line strength and the lower energy level.

$3D- < 3D >$ **express the size of fluctuations, while 3D-1D is related to the treatment of convection (and microturbulence).**

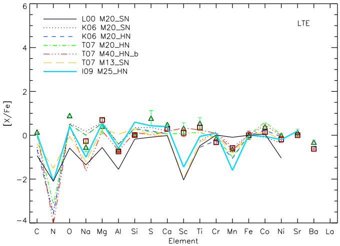
NLTE corrections

Line strength Sr II [mA]	Giant ΔNLTE	Dwarf ΔNLTE
158	-0.14	-0.08
Sr I	0.34	0.34

The corrections are very sensitive to the stellar parameters, the line strength, and majority/minority species. **In general giants have larger corrections than dwarfs.**

What can we learn from stellar abundance patterns? LTE vs NLTE

- Observationally derived abundances for most MP RR lyrae
- The groups of elements trace various supernova (SN) features:
- α-elements serve as tracers of SN Mass (Kobayashi et al 06)
- The α/odd-Z elements provide information on the explosion energy, IMF and SN metallicity
- The amounts of Sc, Ti and Zn are linked to Y_e
- In-/complete Si-burning elements provide clues on the T_{peak}



Hansen et al. 2011

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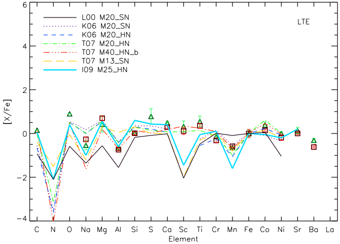
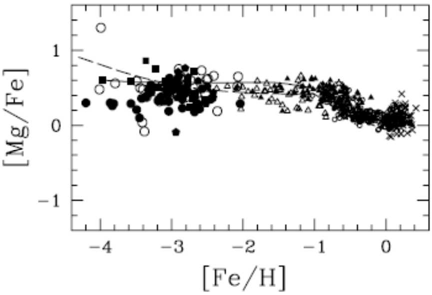


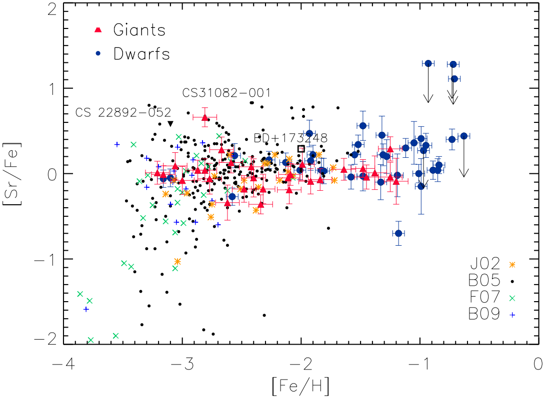
Hansen et al. 2011

Galactic Chemical Evolution - Mg

The Mg lines are strong so we can detect them down to [Fe/H] ~ -4

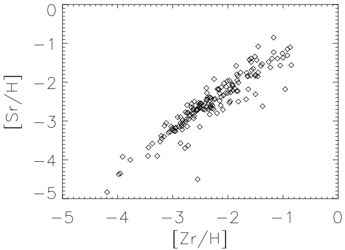


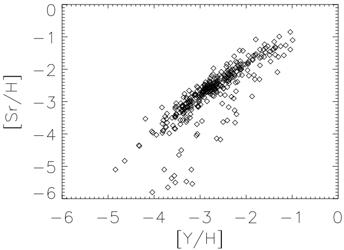
Chemical evolution of Sr



Hansen et al, 2012

Sr, Y, and Zr



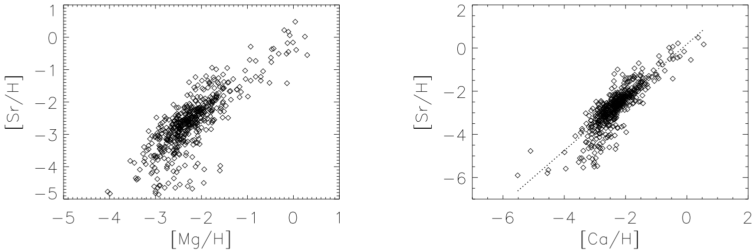


All three elements (Sr, Y, Zr) correlate

Frebel et al, 2010

Correlations

Sr correlate with Mg and Ca (α-element)



Correlation slope ~ 1.2. LEPP region elements could share formation process with α-elements. E.g. α-,n-rich freeze-out?

Frebel et al, 2010

Conclusion

- Accurate high-resolution spectroscopy necessary to derive abundances of heavy elements other than Sr.
- It is important to have NLTE corrections for all abundances, otherwise wrong conclusions on chemical evolution or progenitor generation might be drawn.
- In some cases (for some elements) 3D corrections are even bigger than NLTE corrections. We need 3D+NLTE to have the final/correct abundances.
- The LEPP/weak-r might be related to an 'α-process'
- Mixing processes, 3D self consistent explosions, optimized yields, are essential to understand the information we gain from stellar abundances.
- The large star-to-star scatter dominates any other trend or correction seen for Sr.

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Thank you for listening

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