A stars abundance patterns in open clusters. Constraints on evolutionary models

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Outline

1. Abundances of A and F stars in open clusters
2. Transport processes in stellar interiors
3. Standard evolutionary stellar models
4. Montreal models

Abundances of A and F stars in open clusters (1)

- High resolution high signal-to-noise spectroscopic observations of A and F dwarfs members of several open clusters (same age and initial chemical composition)
- Instruments: AURELIE, ELODIE (R=45000), SOPHIE (R=75000) at OHP, GIRAFFE (VLT)
- Before: abundances [X/H] of A/F stars in OCs unknown apart from [Fe/H] for a few F dwarfs in bright OCs.
- Subject of 3 PhDs: O. Varenne (1996-1999), M. Gebran (2004-2007) and T. Kilicoglu (2011-2014):first uniform analyses assuming LTE of several stars (about 120) well distributed in mass along the Main Sequence in 4 OCs (Hyades, Coma Berenices, Pleiades, M6) and one moving group (UMa)
- Analysis of echelle spectra (3900 Å to 6800 Å) yields access to 22 chemical elements, about 120 observing nights at OHP.
- Selection of 300 lines with high quality atomic parameters and error estimations

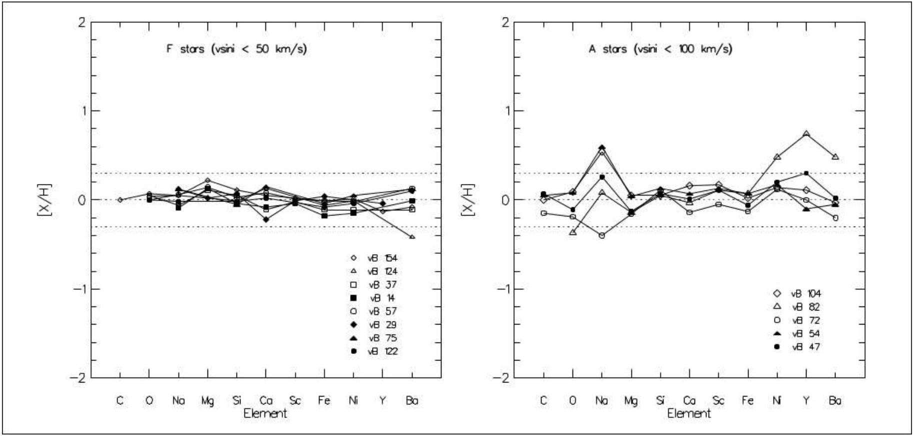
The observed Open Clusters and their characteristics

OC name	Age (Myrs)	Mag	Spectro	References
Pleiades	135	6.5-9.0	ELODIE	Gebran & Monier (2008)
Coma Ber	447	5.0-8.7	ELODIE	Gebran et al (2008)
Praesepe	730	6.3-10.0	ELODIE	Fossati et al (2008)
Hyades	787	4.2-6.9	SOPHIE	Gebran et al (2010)
			AURELIE	Varenne & Monier (1999)
UMa	500	2.0-6.0	AURELIE	Monier (2005)
M6	100		GIRAFFE	Kilicoglu et al (2015)

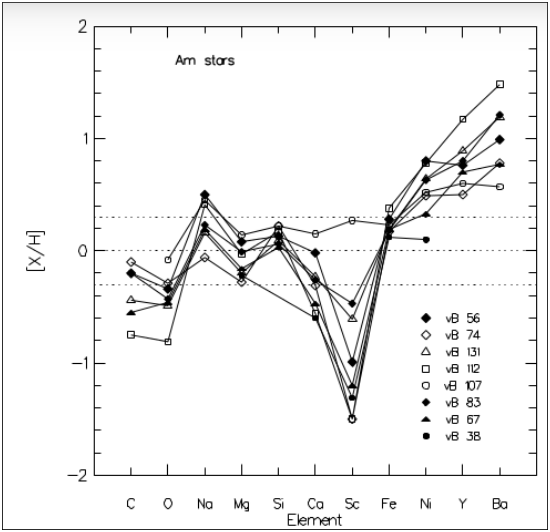
Abundances of A and F stars in open clusters (2)

- A stars exhibit much larger star-to-star variations in their abundances [X/H] versus T_{eff} than F stars do in a given OC.
- Valid for most chemical elements (C, O, Na, Sc, iron-peak, heavy elements): evidence for mixing ?
- the Am stars are almost all deficient in Sc and Ca and rich in Fe, Ni, Y and Ba.
- For several elements [X/H] is correlated with [Fe/H] (si, Mg, Ca, Sc, iron-peak, heavy) but [C/fe] and [O/Fe] are anticorrelated with [Fe/H]
- In the Hyades putative anticorrelation of [X/H] with rotation velocity $v_e \sin i$ for Na, Mg, Si, Ca, Fe, Ni, Ba but not for O, needs confirmation.

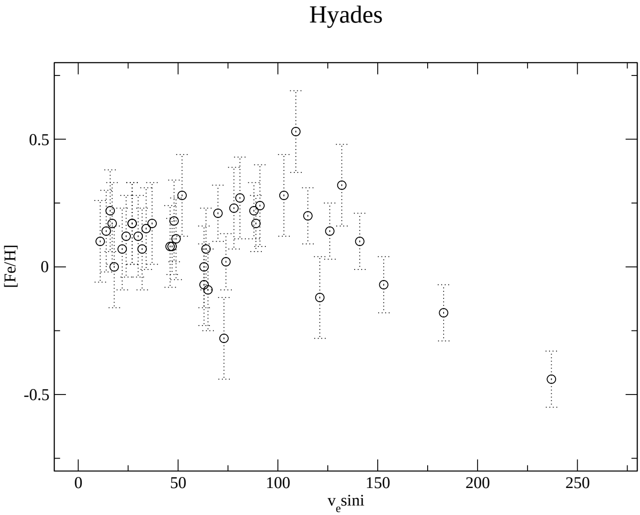
Abundance pattern of the normal A and F dwarfs in the Hyades (VM 1999)



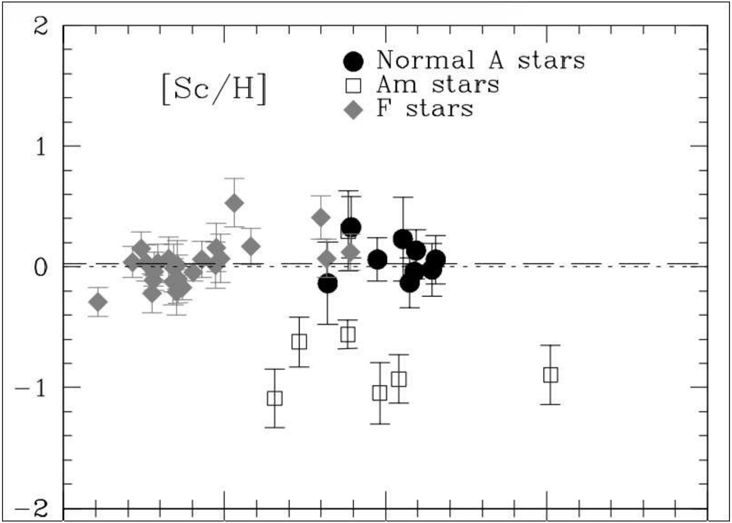
Abundance pattern of the normal Am dwarfs in the Hyades (VM 1999)



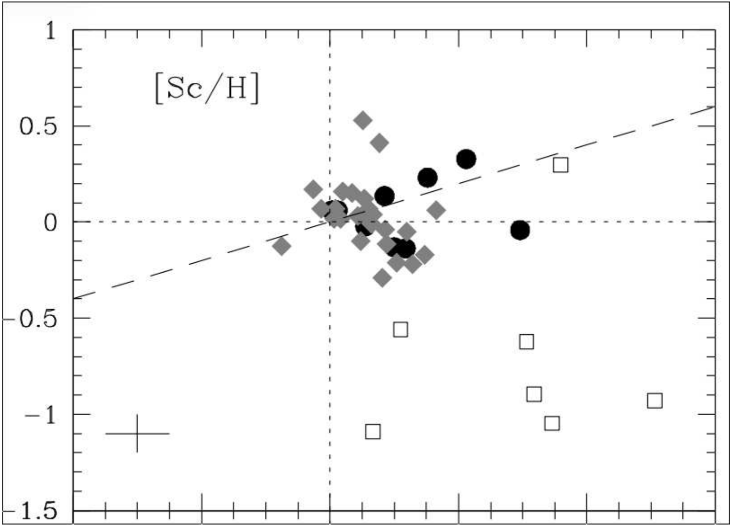
[Fe/H] versus $v_e \sin i$ for the Hyades (Varenne & Monier (1999))



Behavior of [Sc/H] versus Teff for the Hyades (Gebran et al, 2010)



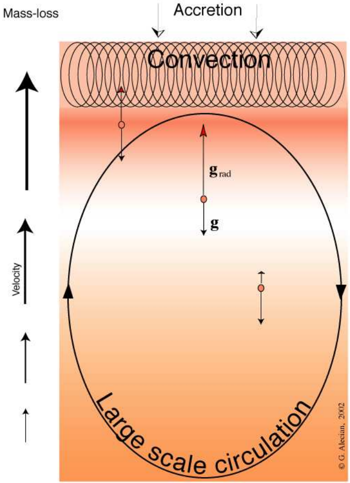
Behavior of [Sc/H] versus [Fe/H] for the Hyades (Gebran et al, 2010)



Transport processes in stellar interiors

- Abundances are sensitive to various transport processes at play in stellar interiors
- Two types of transport processes: separative or mixing
- In slow rotators (CP stars), vertical abundance profile $[X/H](\tau)$ is controled by $g = grad \Longrightarrow$ stratified atmosphere
- In fast rotators (normal A and F dwarfs) rotation mixes the atmosphere (no vertical stratification)

Various transport processes in stellar interiors



Standard evolutionary models

Hypothèses:

- ⋆ Spherical symetry
- ⋆ no rotation
- ⋆ no magnetic field

Equations:

- ⋆ conservation of mass: $\frac{\partial r}{\partial m_r} = \frac{1}{4\pi r^2 \rho}$
- ⋆ hydrostatic equilibrium: $\frac{\partial P}{\partial m_r} = \frac{G m_r}{4\pi r^4}$
- ⋆ energy conservation: $\frac{\partial L_r}{\partial m_r} = \epsilon_{nuc} + \epsilon_g - \epsilon_\nu$
- ⋆ energy transport: convective, semi-convective, radiative

Physics:

- ⋆ equation of state (OPAL 96)
- ⋆ opacities (OPAL 95)
- ⋆ nuclear reaction rates (Caughan & Fowler, 1988)
- ⋆ convection (MLT)

Non standard Montreal evolutionary models (1)

Non standard physics: transport processes

- ⋆ microscopic diffusion
- ⋆ macroscopic transport (turbulent diffusion,...)
- ⋆ Opacities and radiative accelerations are recomputed at each time step for the exact chemical composition in each cell (15000 cells ?) for 28 chemical elements
- ⋆ radiative acceleration for specie A:

$$g_{rad}(A) = \frac{1}{4\pi r^2} \frac{L_{rad}(r)}{c} \frac{\kappa_{Ross}}{X_A} \int_0^\infty \frac{\kappa_\nu(A)}{\kappa_\nu(total)} P(u)du$$

where $\kappa_\nu(A)$: OPAL data (1.5 Go), $\frac{\kappa_\nu(A)}{\kappa_\nu(total)}$: fraction of photons absorbed at each frequency, $P(u)$: black body

Non standard Montreal evolutionary models (2)

⋆ Microscopic diffusion velocity:

$$v_g = D_{12}\{-(A - \frac{Z}{2} - \frac{1}{2})g + Ag_{rad}\}\frac{m_p}{kT} - k_T\frac{\partial \ln T}{\partial r}$$

where k_T is the coefficient for thermal diffusion

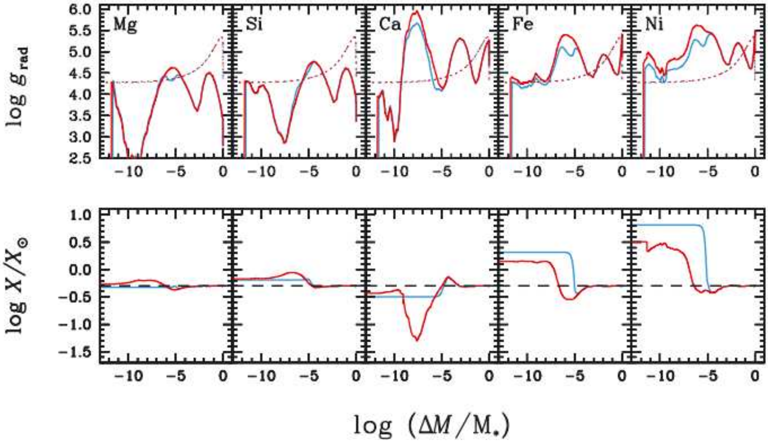
⋆ 1-D transport equation:

$$\rho\frac{\partial c}{\partial t} = \frac{1}{r^2}\frac{\partial}{\partial r}\{\rho r^2(D_{12} + D_T + D_{mix})\frac{\partial c}{\partial r}\rho v_g c\} - S(\rho, T)c$$

- Macroscopic transport: turbulent diffusion:

$$D_T = D_0(He)(\frac{\rho}{\rho_0})^n$$

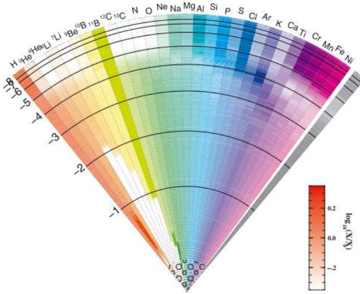
Radiative accelerations and mass fractions for 5 atoms at 232 Myrs for Sirius A (Michaud et al, 2011)

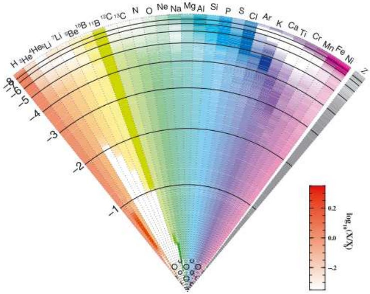


Non standard Montreal evolutionary models (3)

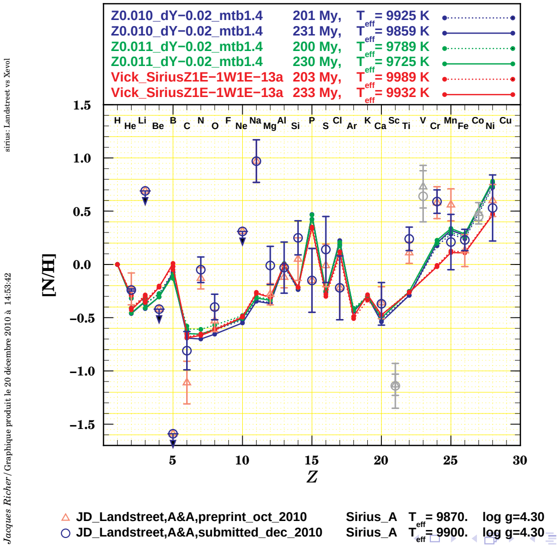
- Diffusion depends on time and initial metallicity
- Diffusion acts over the entire interior
- Chemical anomalies depend of radius
- Pure diffusive models produce underabundances of light elements at the surface
- and overabundances of iron-peak elements
- When compared to "observed" abundance patterns, pure diffusive models reproduce properly the overall shape of the abundance pattern $[X/H] = f(Z)$.
- but light elements abundances (C, N, O) tend to be underestimated and iron-peak abundances overestimated
- Turbulent diffusion is introduced to mix the surface layers.
- parametrized description of mass loss implemented.

Internal structure at 232 Myrs for 2 models of Sirius A (M2011)





Comparison of models to derived abundances for Sirius A (M2011)



Improvements to bring

- ⋆ A full NLTE treatment is required when dealing with resonance lines (Na I, KI, etc...)
- ⋆ Carefully include hyperfine structures of isotopes when relevant and possible.
- ⋆ For the models, other processes could be introduced:
- ⋆ mixing by meridional circulation
- ⋆ internal waves for F stars
- ⋆ predictions for elements heavier than Z=30 are badly needed (useful diagnostics: Sr-Y-Zr triad, Pt, Os, Hg in CP stars)

The End