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Chemical evolution of A– and B–type stars in open clusters: observed abundances vs. diffusion models

Am stars in the Praesepe cluster

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Abstract. We have decided to address the problem of how abundances and peculiarities change during main sequence evolution. We have setup a program to measure the atmospheric abundance patterns from tens of A–type star members of clusters of different ages, and compare the results with theory predictions. In this paper we present the overall project and we focus on the results obtained for a sample of Am stars of the Praesepe cluster ($\log t = 8.85 \pm 0.15$; González–García *et al.*, 2006). We have obtained spectra for eight Am stars, two normal A–type stars and one blue straggler, that are probable members of the Praesepe cluster. For all of these stars we have determined fundamental parameters and photospheric abundances for a large number of chemical elements. For seven stars we also obtained spectra in circular polarisation and applied the LSD technique to measure the mean longitudinal magnetic field. We have found good agreement between abundance predictions of diffusion models and measured abundances, except for Na and S. Li appears to be overabundant in three stars of our sample. No magnetic field was detected in any of the analysed stars.

Key words: stars: abundances – stars: atmospheres – stars: fundamental parameters – stars: chemically peculiar

1. A high–resolution spectroscopic survey of A–type stars in open clusters

The chemical composition of field A–type stars have been studied by several authors, e.g. Hill and Landstreet (1993), Adelman *et al.* (2000). It is not straightforward to use the results of these works to study how chemical elements evolve during the life of the star on the main sequence. This because the original composition of the cloud from which stars were born is unknown and it is not possible to discriminate between evolutionary effects, and differences due to the original chemical composition. Furthermore, it is difficult to estimate the age of field stars with good accuracy, as demonstrate in Bagnulo *et al.* (2006).

Our goal is to determine abundance patterns in A–type star members of clusters of different ages. This is crucial to investigate the chemical differences between normal and peculiar stars inside the same cluster, to study the evolution with time of abundance peculiarities by studying clusters of various ages, to set constraints on the hydrodynamical processes occurring at the base of the convection zone in the non magnetic stars and to study the effects of diffusion in chemically peculiar stars (Fm/Am/Ap/Bp) of the cluster.

We have performed a large observational campaign obtaining high–resolution spectroscopy of a large number of early–type stars in a sample of ten open clusters of homogeneously distributed in age from $\log t = 6.8$ to $\log t = 8.9$. We have performed the observations with the use of five different spectrographs: FLAMES at the ESO VLT, FIES at the Nordic Optical Telescope (NOT), ELODIE and SOPHIE at the Observatoire de Haute–Provence (OHP), and ESPaDOnS at the CFHT. The observed clusters and the instrument used for the observations are listed in Table 1. The chemically peculiar stars of each cluster have already been searched for magnetic field in a previous FORS1 survey (Bagnulo *et al.*, 2006).

We dedicate this first paper to the Am stars of the Praesepe cluster.

2. Observations and analysis of the Am stars of the Praesepe cluster

We observed six stars of the Praesepe cluster using the ESPaDOnS (Echelle SpectroPolarimetric Device for Observations of Stars) spectropolarimeter ($R \sim 65\,000$) at the Canada-France-Hawaii Telescope (CFHT), in polarimetric mode. Spectra of other four stars were obtained with the ELODIE spectrograph ($R \sim 42\,000$) at the Observatoire de Haute Provence (OHP). An additional spectrum was obtained with the MuSiCoS spectropolarimeter ($R \sim 35\,000$) at the 2-m Bernard Lyot Telescope (TBL) of the Pic du Midi Observatory, in polarimetric mode. The spectra were reduced with the pipelines provided for each instrument. The continuum normalisation was performed without the use of any automatic continuum fitting procedure.

Table 1. Open clusters already observed for the survey. The second and third columns give the distance modulus, in magnitudes, and age of the cluster, in $\log t$. The last column shows which instrument (and telescope) were used to obtain the spectra of the stars.

Cluster	Distance Modulus mag.	$\log t$ dex.	Instrument
NGC 6193	11.8	6.8	FLAMES (VLT)
NGC 6383	10.9	6.9	FLAMES (VLT)
NGC 6250	10.8	7.4	FLAMES (VLT)
IC 4665	8.3	7.6	FIES (NOT)
NGC 6405	8.9	8.0	FLAMES (VLT)
NGC 3114	10.0	8.1	FLAMES (VLT)
NGC 5460	9.4	8.2	FLAMES (VLT)
NGC 7092	7.6	8.4	FIES (NOT)
NGC 6633	8.4	8.6	FLAMES (VLT)
M 44 / Praesepe	6.4	8.9	SOPHIE & ELODIE (1.93–m T) ESPaDOnS (CFHT)

The complete sample of stars observed and analysed in this work, together with the adopted set of fundamental parameters are listed in Table 2. Model atmospheres were calculated with the LTE code LLMODELS (Shulyak *et al.*, 2004). We used the VALD database (Piskunov *et al.*, 1995; Kupka *et al.*, 1999; Ryabchikova *et al.*, 1999) as source of spectral line parameters. Convection was treated according to the CM approach (Canuto, Mazzitelli 1992). The fundamental parameters ($T_{\rm eff}$, $\log g$, $\upsilon_{\rm mic}$) were derived spectroscopically using lines of Fe–peak elements and with fitting of Hydrogen lines. Once otained the fundamental parameters, the elemental abundances were derived with direct fitting of the synthetic spectra on the observation. We have synthesised the spectra with Synth3 (Kochukhov, 2006) and fit the core of selected lines to obtain an abundance value for each line. The adopted abundance of a chemical element is the mean of the abundances of the single lines of each element. More details are given in Fossati *et al.* (2007).

We have divided our sample of stars according to the spectral classification given in letterature: normal A–type stars, the blue straggler HD 73666 and Am stars (see Table 2).

2.1. Normal A–type stars

The LSD profile of the normal A–type stars of the cluster (HD 73430 and HD 73575) do not show any magnetic field signature, as it is possible to see in Table 2.

Table 2. Adopted spectroscopic atmospheric fundamental parameters for the analysed stars of the Praesepe cluster. The errors on the fundamental parameters are estimated to be 200 K, 0.2 $\mathrm{km\,s^{-1}}$and 0.2 for $T_{\rm eff}$, $\upsilon_{\rm mic}$ and $\log g$ respectively. The estimated error on $\upsilon \sin i$ is about 5%. The $\upsilon_{\rm r}$ is given in $\mathrm{km\,s^{-1}}$. $\langle B_z \rangle$ indicate the longitudinal magnetic field (measured in Gauss) calculated with the LSD tecnique. The spectral classification is given taking into account our results.

HD	Spectral type	$T_{\rm eff}$ [K]	$\log g$ [cgs]	$\upsilon_{\rm mic}$ [$\mathrm{km\,s^{-1}}$]	$\upsilon \sin i$ [$\mathrm{km\,s^{-1}}$]	$\upsilon_{\rm r}$ [$\mathrm{km\,s^{-1}}$]	$\langle B_z \rangle$ G
73430	A9V	7660	4.02	2.6	73	33.7	1 ± 45
73575	F0III	7300	2.92	2.7	127	33.4	-215 ± 149
73666	A1V	9382	3.78	1.9	10	34.1	6 ± 5
72942	A3V	8450	3.90	2.4	73	39.9	12 ± 31
73045	Am	7570	4.05	3.6	10	27.9	-1 ± 4
73730	Am	8070	3.97	2.6	29	36.6	-12 ± 9
73618	Am	8170	4.00	2.5	47	15.1	–
73174	Am	8350	4.15	2.9	<5	2.9	–
73711	Am	8020	3.69	2.5	62	23.4	–
73818	Am	7232	3.82	2.8	66	22.5	–
73709	Am	8070	3.78	2.3	10	26.7	–

2.2. The Blue Straggler HD 73666

The blue straggler HD 73666 is the hottest star of the cluster and is included in the "New Catalogue of Blue Stragglers in Open Clusters" by Ahumada, Lapasset (2007). This star was classified as normal A1V by Conti *et al.* (1965), as Ap (Si) star by Abt (1985) and as Am star by Andrievsky (1998).

HD 73666 does not show a Si overabundance and magnetic field, as it is for Ap (Si) stars or a Ca/Sc underabundance, as in Am stars. These results bring to the conclusion that HD 73666 is neither an Ap nor an Am star.

2.3. Am stars

The LSD analysis of the Am stars of our sample has not provided any longitudinal magnetic field detection. Our conclusion is that cool Am stars ($T_{\rm eff}$<8500 K) do not have magnetic field that could explain well–known phenomena associated to Am stars, like slow rotation.

The abundance analysis of HD 72942 shows that this star is a normal A–type star and not an Am star. Also membership and/or non-binarity are confirmed. For normal A–type stars and Am stars, the abundances of the Fe–peak elements are different. In normal A–type stars, Fe, Ni, and Cr are solar or slightly underabundant (compared to solar abundances). In Am stars, these elements are slightly overabundant. The Am stars show the characteristic Ca/Sc underabundance together with an underabundance of C, N and O. In all but one stars of our sample, Ba is overabundant, but Ba abundance is definitely lower in nor-

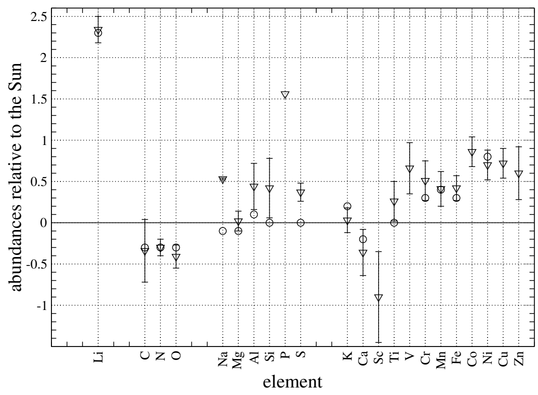

Figure 1. Comparison between the mean abundances of the Am stars of our sample (open triangles) and predicted abundances (open circles) by Richer *et al.* (2000). The derived abundances are relative to the Sun (Asplund *et al.*, 2005). The error bars are the standard deviation from the mean abundance.

mal A–type star than in Am stars. This suggests that Ba may be considered as a further indicator for Am peculiarities, together with C, N, O, Ca, Sc and Fe-peak elements.

3. Comparison with diffusion models

Underabundances of Sc and/or Ca and little overabundances of iron-group elements are qualitatively explained by diffusion theory (see, e.g., the review in the introduction by Alecian, 1996 and references therein).

The results of our abundance analysis can be used to constrain diffusion models. We can also compare our results with theoretical predictions. For the comparison we have calculated the mean abundances of the Am stars for the analysed elements till Zn and taken predicted abundances from Figure 14 of Richer *et al.* (2000). The comparison is shown in Fig. 1.

Fig. 1 shows an agreement for Li, C, N, O, Mg, Al, Si, Ca and Fe–peak elements within 0.1 dex. Discrepancies are apparent for Na and S (Sc was not modeled by Richer *et al.* (2000) because no OPAL data were available for Sc).

Na is the element for which the derived mean abundance ($\simeq 0.5$ dex with respect to the solar abundance) has the smallest scatter, among the Am stars of our sample. Observations seem definitely to suggest an overabundance of this element which is inconsistent with a model prediction of -0.1 dex.

Also S shows a small scatter in our sample ($\sigma = 0.11$ dex). Kamp *et al.* (2001) determined the S abundance in the metal poor A–type star λ Boo in LTE and non-LTE. Their analysis shows that the S abundance determined in non-LTE is lower than the one determined in LTE by 0.1 dex. For metal poor stars non-LTE effects are larger than for normal A–type stars and Am stars. This brings our S abundance ($\simeq$ +0.35 dex) to an overabundance (relative to the Sun) of $\geq$0.25 dex, compared with a solar abundance predicted by Richer *et al.*, (2000). This apparent discrepancy should be investigated in non-LTE regime.

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