The A-star puzzle
Proceedings IAU Symposium No. 224, 2004
J. Zverko, J. Žižňovský, S.J. Adelman, & W.W. Weiss, eds.

DOI: 10.1017/S1743921304004570

Abundances of A/F and Am/Fm stars in open clusters as constraints to self-consistent models including transport processes

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Abstract. We describe the current status of a programme we started a few years ago to observe a large number of A/F and Am/Fm stars in open clusters of various ages. Spectra were obtained with the AURELIE and ELODIE spectrographs at a resolving power of about 40000 and S/N ratios from 100 up to 500. Abundances of 11 chemical elements have been derived by using Takeda's (1995) procedure. A short review on previous abundance determinations of A and F dwarfs in open clusters and a progress report on the current status of this project are presented. New abundance determinations for 24 A and F dwarfs in the Coma Berenices cluster are presented. These abundance determinations serve to set constraints to self-consistent evolutionary models of A and F stars including transport processes.

Keywords. Diffusion, stars: abundances, stars: chemically peculiar, open clusters and associations: individual: (Coma Ber)

1. Introduction

A few recent studies have addressed the chemical composition of the A and F dwarfs in the brightest open clusters. High quality high resolution spectroscopy is now feasible with 2 meter-class telescopes for the nearest clusters. Spectrum synthesis is the most appropriate method to derive abundances for A and F stars, some of which are fast rotators. Ultimately these abundance determinations can help constrain models of the internal structure of these stars. The Montreal group has recently developed models predicting the evolution of 28 chemical elements for A and F stars consistently with the internal structure (Turcotte *et al.* 1998, Richer *et al.* 2000, Richard *et al.* 2001). These new models include the effects of radiative diffusion and gravitational settling for all species having OPAL opacities. Provided overshooting homogenizes the surface regions, the predicted abundances are larger by a factor of 3 than the ones derived from the observations. Turbulent transport has been added to improve the agreement. For stars in clusters, the comparison of the abundance pattern (i.e., [X/H] versus Z) predicted by these models with those derived from observed spectra helps to set constraints on the processes included into the models.

The main thrust of this paper is to review the current knowledge on the abundances of A and F dwarfs in various open clusters, present a progress report on our programme to observe a large number of these stars well distributed in masses in selected open clusters. New abundance determinations for 13 A and 11 F dwarfs in the Coma Berenices cluster are presented. We also briefly discuss comparisons of predicted abundances with those derived from the spectra.

2. Previous abundance determinations of A and F stars in open clusters

A and F main sequence stars in open clusters are useful objects to constrain transport processes in time-dependent models. In contrast with the field stars, stars in clusters all have the same age and the same initial chemical composition (which can be derived from the G dwarfs in the cluster). Very few studies have so far addressed the chemical composition of A stars in open clusters and they usually have focused on a very limited numbers of stars not necessarily well distributed in mass along the Main Sequence. For the Hyades cluster, Burkhart & Coupry (1989) found the abundances of Li, Al, Si and Fe for 5 Am and 1 A star. Takeda & Sadakane (1997) derived the abundances of O and Fe for 8 Am and 10 normal stars and Hui-Bon-Hoa & Alecian (1998) those of Mg, Ca, Sc, Cr, Fe and Ni for 4 Am and 2 normal A dwarfs. Varenne & Monier (1999) determined the abundances of 11 chemical elements (C I, O I, Na I, Mg I, Si I, Ca I, Sc II, Fe I, Ni I, Y II, Ba II) for a much larger sample of stars: 19 A/Am dwarfs and 29 F dwarfs using AURELIE spectra centered at three wavelengths (λ6160, λ5080 and λ5530). These stars are regularly distributed in spectral type along the Main Sequence to sample the expected masses uniformly. All these stars were analysed in a uniform manner using spectrum synthesis as a few of them are fast rotators. The effective temperatures and surface gravities were derived using Napiwotzki *et al.*'s (1993) revision of the UVBYBETA code. The line list was constructed from lists retrieved from VALD and from Kurucz's web site. We carefully checked the quality of the atomic parameters using the NIST database and also by synthesizing the spectrum of the Moon and that of Procyon. Given an appropriate model atmosphere, Takeda's (1995) iterative procedure yields the abundances, the microturbulent velocity and $v_{\rm e} \sin i$. For the Hyades, Varenne & Monier (1999) found large star-to-star variations for the normal A stars in particular for O, Na, Ni, Y and Ba. The Am stars are almost all deficient in Sc and Ca and overabundant in Fe, Ni, Y and Ba and also show star-to-star variations. In contrast, the F stars show very little scatter in their abundances. The A stars show a much larger scatter than the F stars on graphs displaying the abundances of individual elements [X/H] versus the effective temperature ($T_{\rm eff}$). No convincing anticorrelation between the abundances and rotationnal velocity ($v \sin i$) was found. Note that significant abundance differences have been found among the few field A stars analysed so far (Hill 1995, Hill & Landstreet 1993, Holweger *et al.* 1986, Lambert *et al.* 1986, Lemke 1989,1990, Rentzsch-Holm 1997, Varenne 1999).

For convenience, we have gathered previous abundance determinations for the A and F dwarfs of the Coma Berenices cluster in Table 1. A similar list collecting all abundance determinations in the Hyades can be found in Table 1 of Varenne & Monier (1999).

3. Status of the project and data reduction

In our observational programme, we ultimately intend to acquire high resolution ($R = 40000 - 60000$) high S/N spectra of all A and F stars in several open clusters: IC 2391, α Persei, the Pleiades, Coma Berenices, Praesepe and the Hyades. We have excluded Ap stars since the models we wish to constrain do not include the effects of a magnetic field. In these clusters, the A and F dwarfs which range in magnitude from $V = 5$ to $V = 11$ are observed with 2-m telescopes. They sample the expected mass range from A0 V to F9 V along the main sequence. Spectra with S/N ratios ranging from 100 to 500 were obtained first with the AURELIE monorder spectrograph at the Observatoire de Haute Provence (OHP, France) for α Per, Coma Berenices and the Hyades. Three spectral regions centered on λ6160 (region 1), λ5080 (region 2) and λ5530 (region 3)

Table 1. Previous abundance determinations for the Coma Ber A, F and G dwarfs.

Reference	Stars studied	Chemical Elements
Savanov (1996)	13 A-Am and F-Fm	C, O, Si, Ca, Fe, Ba
Hui-Bon-Hoa *et al.* (1997)	2 A-Am	Mg, Ca, Sc, Cr, Fe, Ni
Hui-Bon-Hoa & Alecian (1998)	4 A-Am	Mg, Ca, Sc, Cr, Fe, Ni
Burkhart & Coupry (2000)	7 A-Am	Li, Al, Si, S, Fe, Ni, Eu
Boesgaard (1987)	22 A and F	Li
Friel & Boesgaard (1992)	14 F	Fe, C
Jeffries (1999)	15 F, G, K	Li
Soderblom *et al.* (1990)	28 G	Li

have been selected as they include several lines having accurate oscillator strengths for the chemical elements we study. These regions were those observed by Edvardsson *et al.* (1993) in their spectroscopic survey of F dwarfs in the galactic disk. We are currently reobserving these three clusters and the Pleiades and Praesepe with the ELODIE echelle spectrograph (also at OHP) in the range $\lambda 3920$ to $\lambda 6800$ to have access to a much larger number of spectral lines. The selected open clusters of our programme and the current status of their observations and analysis are collected in Table 2. Note that we have also started analysing the UVES spectra for IC 2391 which we retrieved from the POP archive (Bagnulo 2005).

Table 2. Selected open clusters

Cluster ID	Age (Myrs)	Mag	$N_\star$	Spectrograph	Observed	Analysed
IC 2391	45	7.0-9.0	20	UVES	POP	yes
α Per	71	7.6-11.0	52	AURELIE	19	no
Pleiades	135	6.5-9.0	49	ELODIE	19	no
Coma Ber	447	5.0-8.6	68	AURELIE	24	yes
				ELODIE		no
Praesepe	730	6.3-10.0	80	ELODIE	10	no
Hyades	787	4.2-6.9	48	AURELIE	48	yes

4. New results for the Coma Berenices cluster

The results presented here were obtained by synthesizing AURELIE spectra in the 3 spectral regions 1, 2 and 3 mentioned above. The MIDAS software was used to reduce all the AURELIE spectra following the standard procedure (offset removal, division by the flat field, wavelength calibration). The spectra of the narrow lined stars were used to select continuum windows through which cubic splines were interpolated. The spectra were then normalised to this continuum. Continuum windows are very narrow for the fast rotators (but there are very few in Coma Berenices) and the normalisation is less secure for these stars. To derive abundances, we have adjusted synthetic spectra to the observed spectra using Takeda's (1995) iterative procedure as described in Varenne & Monier (1999).

We have first checked the spectral synthesis on Procyon whose abundances are fairly well known (Steffen 1985).The abundances we derived have been compared to those determined by Steffen (1985) and Edvardsson *et al.* (1993). The differences

$$\Delta[\mathrm{X/H}] = [\mathrm{X/H}]_{\text{this study}} - [\mathrm{X/H}]_{\text{other}} \tag{4.1}$$

are less than 0.1 dex for 8 out of 11 elements and less than 0.15 dex for the 3 remaining (C , Y and Ba) (see Varenne & Monier 1999).

The abundances for the 24 Coma Berenices stars relative to the Sun

$$([\mathrm{X/H}] = \log{[\mathrm{X/H}]_{\star}} - \log{[\mathrm{X/H}]_{\odot}}) \tag{4.2}$$

are collected in Figure 1.

An accurate assessment of the uncertainties of the abundances is mandatory if one wishes to constrain usefully the predictions of the models. The main sources of uncertainties for the abundances stem a priori from those of the effective temperatures, surface gravities, microturbulent velocities, oscillator strengths and apparent rotational velocities which are assumed to be independent. A change of $\Delta \log g = +0.2$ dex induces a very small change in the abundances ($\simeq 0.04$ dex) whereas an increase of 200 K of $T_{\rm eff}$ induces a larger change (~ 0.10 dex). Adding the inaccuracy on the oscillator strengths and apparent rotational velocities and continuum placement for fast rotators typically enhances the uncertainties of the relative abundance up to at least $0.30 - 0.40$ dex. The reader should be aware that the uncertainties in Figure 1 are lower limits (see Varenne & Monier (1999) for a complete discussion of the errors).

Table 3. Abundances for A and F dwarfs in Coma Berenices

HD	SpT	C I	O I	Na I	Mg I	Si I	Ca I	Sc II	Fe I	Ni I	Y II	Ba II
106103	F5V		−0.40	−0.21		−0.14	−0.19		−0.32	−0.24		−0.08
106293	F5V		−0.11	−0.14		−0.22	−0.21		−0.31	−0.34		0.00
106691	F5IV	(−0.1)	−0.46	−0.12	−0.11	−0.10	−0.16	−0.33	−0.23	−0.31	−0.29	−0.23
106946	F2V		0.00	−0.04		−0.20	−0.27		−0.38	−0.45		−0.16
107611	F6V		−0.44	−0.29		−0.15	−0.18		−0.18	−0.22		0.04
107877	F5V	−0.15	−0.35	−0.13		−0.11	−0.11		−0.14	−0.20	−0.15	0.13
108154	F8V		−0.13	−0.26	0.04	−0.13	−0.16	−0.05	−0.18	−0.19		0.21
108226	F5	−0.10	−0.12	−0.19		−0.09	0.06		−0.14	−0.13	−0.17	0.43
108976	F6V		−0.60	−0.14	0.08	−0.05	0.05	0.03	−0.06	−0.13		0.37
109069	F0V	−0.18	−0.32	−0.56	−0.26	−0.21	−0.41	0.04	−0.41	−0.29	−0.26	−0.39
109530	F2V	−0.20	−0.06	−0.08	−0.10	−0.19	−0.32	−0.07	−0.36	−0.30	−0.18	−0.20
106887	A4m				−0.22		(−0.42)	−0.73	0.06			
106999	Am	(0.00)	−0.15	−0.02	0.04	0.02	0.01	0.07	−0.02	0.27	0.07	0.03
107131	A6IV-V/ A4IV-V		−0.14	−0.92		−0.13	−0.18		−0.28	−1.00		−0.36
107168	A8m/ kA5hA5mF0	−0.61	−0.46	0.07	0.18	0.22	−0.02	−0.02	0.20	0.69	0.78	0.96
107276	Am/ kA5mA7	0.10	−0.21	−0.25	−0.25	0.07	−0.23	−0.07	−0.19	−0.62	0.00	−0.12
107513	Am/ kA7hF0mF0	−0.10	−0.16	−0.55	−0.45	−0.39	−0.44	−0.24	−0.53	−0.58	−0.16	−0.45
107655	A0V	−0.12	−0.55		−0.12	−0.15	−0.26	−0.69	0.11	0.68	0.63	0.80
107966	A3V/A3IV	−0.05	−0.04	0.53	0.01	−0.19	0.02	−0.02	−0.13	0.01	0.05	−0.06
108382	A4V/A3IV	−0.05	−0.12	0.07		−0.20	−0.13		−0.23	−0.46	0.01	−0.16
108486	Am/ kA3hA5mA7	−0.40			0.07		−0.16	−0.83	0.28	0.48	0.94	
108642	A2m/ kA2hA7mA7	−0.61	−1.00	0.24		−0.07	−0.56		0.03	0.52	0.50	0.60
108651	Am	−0.60	−0.57	0.24		0.10	−0.61		0.34	0.59	0.64	1.50
109307	A4m/ A3IV-V	−0.29	−0.30	−0.27	−0.25	−0.11	−0.14	0.10	−0.10	0.17	0.44	0.22

As for the Hyades, we find very little scatter for the abundances of the F dwarfs in Coma Berenices. The mean iron abundance for the F dwarfs in Coma Ber is slightly below solar in very good agreement with Boesgaard (1989). The A dwarfs exhibit large star-to-star variations in [Na/H] and [Ni/H], but less in [Si/H]. The Am stars all are deficient in oxygen. Most have overabundances in Ni, Y and Ba. No convincing trend of the abundances [X/H] versus $T_{\rm eff}$ nor [X/H] versus $v_e \sin i$ are found. The A stars exhibit a much wider scatter than the F stars in [X/H] versus $T_{\rm eff}$.

5. Constraints on transport processes

Several types of processes are expected to affect the surface abundances of A and F dwarfs: radiative diffusion, gravitationnal settling, meridional circulation, wind, accretion (Michaud 2005). The most recent models (Richer *et al.* 2000, Richard *et al.* 2001, Michaud 2005) take into account the atomic diffusion of metals and the radiative accelerations for all species having OPAL opacities. In these models, iron-peak convection zones appear at temperatures close to 200000 K. Assuming that overshooting homogenizes the surface regions, the abundances predicted by the models are usually 3 times larger than the abundances derived from the spectroscopy. Turbulent transport has been added to improve the agreement. The anomalies appear then to depend on the depth of the zone mixed by turbulence. Detailed comparison of the model predictions with derived abundances for individual stars are presented in Richer *et al.* (2000) (see for instance their figure 19 for the Hyades star 68 Tau). While the models fail to predict the abundances for each species, they do reproduce the shape of the abundance pattern. For a given star, there usually is considerable scatter between the abundances derived by different authors. The sources for this discrepancy are many: use of different methods to derive the abundances (curve-of-growth versus spectral synthesis), use of different codes and/or assumptions to model the atmosphere and the spectrum, use of different effective temperatures, surface gravities, atomic parameters. Processes not yet included in the models such as differential rotation or differential mass loss (Michaud *et al.* 1983) might also account for the disagreements.

6. Conclusions

To constrain the current models, abundances must be determined in a uniform manner for a large number of A and F stars well distributed in mass in clusters of various ages. Abundances are needed for as many chemical species as possible for $Z \leqslant 30$ with errors properly assessed. In Coma Berenices, we find evidence for large star-to-star variations in the normal A stars and in the Am stars as in the Hyades. There is very little scatter in the F dwarfs in both clusters. We believe that the differences in abundances among the A stars born from the same original interstellar matter may be the signature of the occurence of transport processes in their interiors. Observations with UVES of A and F dwarfs in more distant clusters sampling the age sequence a few 10 Myrs up to 800 Myrs are highly desirable.

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Discussion

NOELS: Have you checked and analysed the abundances in the lowest mass stars of your clusters? This would be interesting because it would give better knowledge of the composition of the original cloud and by comparing them with the A and F stars of your samples, it would give a quantitative estimation of the effect of diffusion.

MONIER: The late type F stars are the most difficult to observe on 2-m class telescopes because they are faintest. I have indeed observed them for the closest, i.e., brightest clusters.