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Behaviour of calcium abundance in Am-Fm stars with evolution*

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Abstract. Calcium abundance in the atmosphere of Am stars is examined as a function of their evolutionary state within the main sequence. New spectroscopic abundances as well as abundances obtained photometrically by Guthrie (1987) are used, since they are mutually quite consistent.

The main result of this work is that, contrary to earlier suggestions, calcium abundance does not tend to be larger in evolved Am stars than in unevolved ones, for objects distributed along a given evolutionary track in the HR diagram. The trend appears to be the reverse, if it is present at all.

For our whole sample of Am stars, there is a significant correlation between calcium abundance and effective temperature, in the sense that the cooler objects are the most Ca-deficient, hance have the most pronounced Am peculiarity. This implies an apparent correlation between calcium deficiency and age, although the lack of Am stars younger than $\log t = 8.6$ seems real. Our results are fully consistent with the low rate of Am stars observed in young clusters and with theoretical predictions of time-dependent radiative diffusion (Alecian 1996).

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

1. Introduction

The Am-Fm stars, whose effective temperature lies between 7000 K and 9000 K, are the coolest chemically peculiar stars on the main sequence (excluding barium or carbon dwarfs, which owe their peculiarity to binary evolution). Their main characteristics are an underabundance of calcium and scandium (about 5 to 10 times lower than in the Sun), a slight overabundance of iron-peak elements, a slow rotational velocity ($v \sin i \leq 100$ km s^{-1}) and a high rate of tight binaries (Abt and Levy 1985).

To explain the emergence of chemical anomalies in Am stars, one usually invokes the radiative diffusion theory developed by Michaud et al. (1983). This theory predicts that, in a slowly rotating star where the large-scale meridional circulation is weak enough, helium is no longer sustained and flows inside the star, gradually disappearing from the atmosphere. The diffusion process could therefore take place just below the thin H I convective zone where the diffusion time is short with respect to the stellar lifetime; as a first approximation, the chemical elements whose radiative acceleration is larger than gravity become overabundant and, in the opposite case, underabundant.

The H I convective zone becomes deeper as the star evolves on the main sequence; finally, the c.z. may dredge-up calcium and scandium, leading to the normalisation of the surface abundance. Berthet (1992), using data for Am members of three open clusters, provided some evidence for a trend between calcium abundance and evolutionary stage in agreement with the preceding scenario; Guthrie (1987) had already suspected such a trend in a sample of field Am stars. Berthet (1992) proposed an evolutionary scenario for the Am stars by considering also the δ Del stars (which have the same abundance anomalies as the Am stars except for Ca and Sc which are not deficient) and the metallic A and F giants discovered by Hauck (1986) on the basis of their enhanced blanketing parameter Δm_2 of Geneva photometry: an Am star would evolve into a δ Del and finally into a metallic F giant, following a sequence of increasing Ca abundance. However, a comparison of multiplicity and rotational velocities of metallic A-F giants and of Am stars has shown that the latter cannot be the progenitors of the former, which casts serious doubts upon Berthet's scenario (Künzli & North 1997).

Alecian (1996) has studied theoretically the evolution of calcium abundance in the early stages of slowly rotating A and F type stars. His work predicts a short phase of calcium overabundance (before $\log t = 8$) followed by a phase of underabundance for some depth values of the mixing zone which is just below the H I convective zone. According to this result, all slowly rotating A and F stars go through a phase of underabundance of Ca, but only after 10^8 years. This prediction is supported by North (1993), who pointed out a deficiency of Am stars in young open clusters.

One goal of the present work is to test the results of Berthet (1992) and Guthrie (1987). Another is to determine, as far as possible, the evolutionary state at which slowly rotating A and F stars become Am stars. The knowledge of this parameter may

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* Based on observations collected at Observatoire de Haute Provence (CNRS), France, and on data from the ESA HIPPARCOS astrometry satellite.

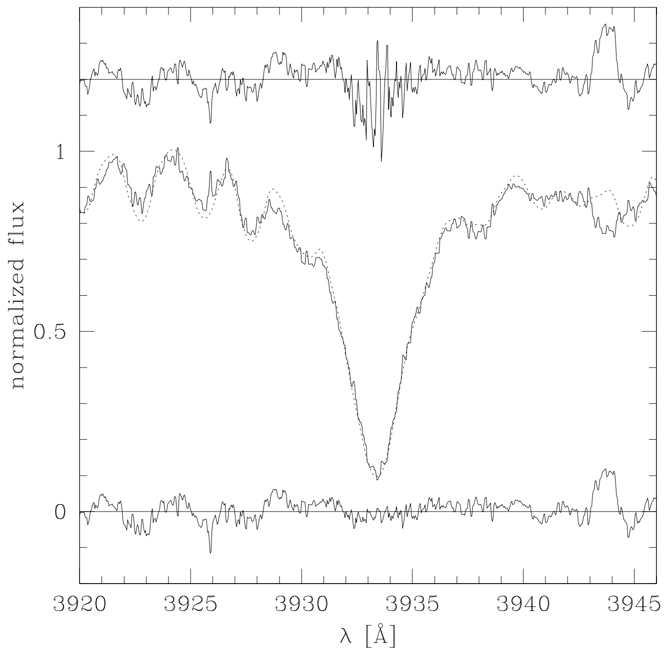

Fig. 1. AURÉLIE spectrum of the Am star HD 74190 in the vicinity of the Ca II K line. The synthetic spectrum (dotted line) with $T_{\rm eff}$ = 7944 K, log g = 3.84 dex, [M/H] = -0.22 dex, ξ_t = 3.3 km s^{-1} and v sin i = 58 km s^{-1} is shown together with the observed one (continuous line). The ratio (increased by 0.2 for clarity) of the observed and synthetic spectra is shown at the top of the figure, while the difference is shown at the bottom. The synthetic spectrum is computed with log($\frac{N_{\rm Ca}}{N_{\rm H}}$)+12 = 6.28.

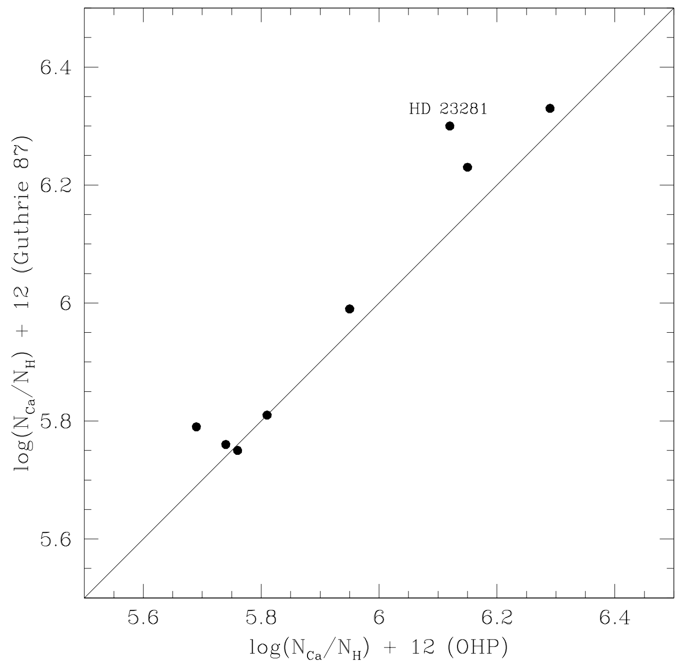

Fig. 2. Comparison between Ca abundances obtained by Guthrie (1987) and those obtained in this paper. The dispersion of the points from the straight line at 45 degrees is 0.07 dex.

shed some light on the formation of Am stars. To this end, we measured at OHP some known bright Am stars whose Ca abundance were then determined by optimum fit of synthetic spectra to our observed ones, taken in the region of the Ca II K line. To this sample we added the 57 stars of Guthrie (1987) whose Ca abundance was determined from the photometric k index and is well-correlated with ours for the eight common stars. For each star, we determine the effective temperature from Geneva photometry (Künzli et al. 1997) and the absolute magnitude (corrected for duplicity) from the Hipparcos parallax. Then, in the HR diagram we compute the evolutionary state (defined by our D_{1000} parameter) and the age and mass by interpolation in the evolutionary tracks of Schaller et al (1992).

2. The sample and observations

We have selected Am stars between 1.5 and 2 solar masses at different distances from the ZAMS in order to follow the calcium abundance with evolution. The objects selected come from the catalogue of Hauck & Curchod (1980) which contains 385 Am stars with known spectral type. We have added some metallic giant F stars (Hauck 1986) and normal A stars as reference stars. Because of bad weather, we could observe only 27 Am stars, 2 metallic giant F stars and 2 normal stars.

Our observations were made during two sessions of a few nights' duration each at Observatoire de Haute-Provence (OHP) in May 1994 and in November 1995, using the 1.52m telescope equipped with the AURÉLIE spectrograph (Gillet et al. 1995). The detector is a double-element TH7832 with sets of 2048 photodiodes of 750 x 13 μm. We used the grating N^o 2 with 1200 lines/mm; the spectra were thus obtained at a reciprocal dispersion of 8 Åmm^{-1} in the spectral region centered on the Ca II K line [3820Å, 4035Å]. Using calibration spectra of thorium, the reduction was made at Geneva with MIDAS procedures for the first mission and at OHP with IHAP procedures for the second mission. To normalise our spectra, we simply fitted a straight line to the continuum. For most spectra, a signal-to-noise ratio of 150 was achieved in the continuum.

3. Calcium abundance

For the same reasons as those invoked by Berthet (1992), we use the strong Ca II K line to determine the abundance of this element. In the atmospheres of Am stars, most of the calcium is ionised due to a low first ionisation potentiel, thus the assumption of LTE may fail for the neutral calcium lines. However, the wings of the Ca II K line are formed deeper in the atmosphere than the other lines of ionised elements, making the LTE assumption more valid because the density of this ion is higher and the transition comes from the ground state. In addition, this line is always visible even when the star rotates rapidly.

The synthetic spectra are computed using the SYNSPEC code of Hubeny et al. (1993) and Kurucz atmosphere models (1995). The Stark, van der Waals and radiative widths are those

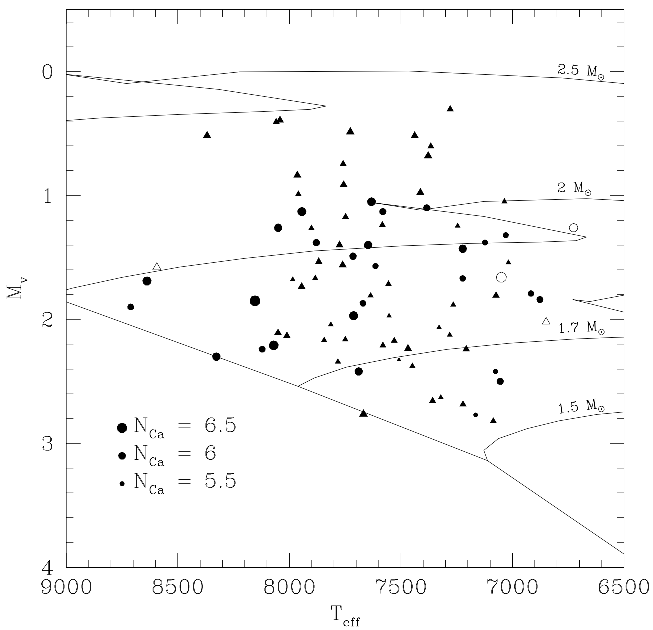

Fig. 3. HR diagram of the 76 Am stars included in the discussion. The absolute magnitudes are deduced from Hipparcos parallaxes and corrected for duplicity. The effective temperatures are taken from Künzli et al. (1997). The stars measured at OHP are represented by black circles and those of Guthrie (1987) by black triangles. The other stars measured at OHP are represented by open circles for giant metallic F stars and by open triangles for normal stars. The size of the points is related to the Ca abundance.

calculated by Kurucz (1989) for iron-peak elements lines. The adopted parameters $T_{\rm eff}$ and $[M/H]$ for the atmosphere models come from the colours obtained in the Geneva photometric system for all stars of the sample, using the calibration by Künzli et al. (1997). For all Am stars, the surface gravity $\log g$ is deduced from the HIPPARCOS parallax and from the apparent V magnitude, while the mass is obtained by interpolation in the evolutionary tracks of Schaller et al. (1992). For normal and giant metallic stars, $\log g$ is determined from Geneva photometry (Künzli et al. 1997). The microturbulence ξ_t is calculated from Edvardsson et al. (1993) or Coupry & Burkhart (1992) according to the effective temperature and the surface gravity of the star. The spectra were then convoluted by a gaussian with $FWHM$ = 0.379 Å representing the instrumental profile and by the appropriate rotational profile. The $T_{\rm eff}$, $\log g$, $[M/H]$, ξ_t and $v \sin i$ values are listed in Table 1 for the stars observed at OHP. The Ca II K spectral type given in this table comes from the catalogue of Hauck & Curchod (1980) and the $v \sin i$ from Abt & Morrell (1995) or the Bright Star Catalogue (Hoffleit & Jaschek 1982). In most cases, the $v \sin i$ values taken from the literature are completely compatible with our spectra. But in a few instances, the attempt to fit the observed spectrum with the synthetic one failed, when the latter was convoluted using the $v \sin i$ from the literature; in such cases (or when $v \sin i$ was previously unknown), we used our own estimate, which is quite reliable because it is based not only on the Ca K line, but also on many metallic lines spread over the 200 Å wavelength range.

When fitting a spectrum, only two parameters remain free, that is the rotational velocity and of course the calcium abundance. The effective temperature, surface gravity, metallicity and microturbulence are fixed. The photometrically determined $T_{\rm eff}$ is confirmed by the fit of the Balmer lines H_η, H_ζ and H_ϵ in our spectra, so we did not attempt to change its value, although these lines are computed using a simplified broadening theory only and not the VCS theory. The calcium abundance essentially affects the wings of the K line, because it is saturated. The rotational velocity acts on the depth of the line, the wings being only weakly affected. The quantitative effects of the effective temperature, rotational velocity and calcium abundance are shown on Figs. 3, 4 and 5 of Berthet's paper (1992) respectively (he used the ADRS code – see Chmielewski 1979, Lanz 1987 – but one sees of course the same behaviour with SYNSPEC). For the above reasons, we determine the Ca abundance essentially by a fit on the wings and then on the depth of the K line. The resulting Ca abundances are given in Table 1. The internal precision is estimated at about 0.1 dex. As an exemple, Fig. 1 shows the optimal fit of HD 74190 by a synthetic spectrum in the region of the Ca II K line (3933.663 Å). This fit leads to a relative abundance $\log(\frac{N_{\rm Ca}}{N_{\rm H}}) + 12 = 6.28$.

Our determinations were tested with the eight stars we have in common (HD 18557, HD 23281, HD 40062, HD 60652, HD 71297, HD 136403, HD 221675, HD 223461) with Guthrie (1987), who measured the Ca abundance photometrically by the k index. Fig. 2 compares the Ca abundances of Guthrie with those determined at OHP. Except for HD 23281 which shows a difference of 0.18 dex between Guthrie's value and ours, there is an excellent correlation. The rms scatter around the straight line at 45 degrees is only 0.07 dex. For this reason, we include Guthrie's sample in our discussion. Guthrie estimates his overall error on Ca abundance at about ± 0.3 dex, but it is probably less.

4. Discussion

As part of the discussion will depend on the position of Am stars in the HR diagram, it is necessary to present their fundamental parameters in more details.

The effective temperature is photometrically determined by the calibration of the Geneva system (Künzli et al. 1997) which uses both stars with known fundamental parameters and atmosphere models (Kurucz 1993, 1994, 1996a, 1996b). The only drawback of the Geneva system, compared to the $uvby\beta$ one, is its sensitivity to interstellar reddening for A and cooler stars. But, as all 76 Am stars are bright ($m_v \leq 7$ mag.), IS reddening is negligible. The fundamental stars used in this range of temperature are essentially those of Blackwell & Lynas-Gray (1994), who relied on the infrared flux method. These authors give an estimated error of about 2%.

The absolute visual magnitudes are deduced from Hipparcos parallaxes of Am stars (Proposal 55). For the two metallic F giants and the two normal stars, the absolute magnitudes are taken from the calibration of Hauck (1973). For these stars, M_v is preceded by an asterisk in Tables 1 and 2. As the stars considered are bright, hence near to us, the relative error on

Table 1. Abundances of Ca for the sample of Am-Fm stars. The uncertainties on $\log t$ are propagated from assumed errors on $T_{\rm eff}$ and $\log g$ of 270 K and 0.18 dex respectively (Asiain et al. 1997), which are comfortably large. An asterisk indicates that M_v was determined not from Hipparcos parallaxes, but from Geneva photometry.

HD	ST Ca ii K	Rem.	$T_{\rm eff}$ [K]	$\log g$	[M/H]	$v\sin i$ [km s^{-1}]	ξ_t [km s^{-1}]	M_v	$\log(\frac{N_{\rm Ca}}{N_{\rm H}})+12$	M [M$_\odot$]	$\log t$	D_{1000}
861	A2m	SB1	7715	3.90	0.29	35	3.2	1.49	5.95	1.98	8.934 ± 0.050	1.285
2628	A5m	-	7223	3.77	-0.14	20	2.7	1.43	6.15	1.98	8.992 ± 0.081	1.800
15385	A5m	V	8154	4.12	0.00	21	3.4	1.85	6.61	1.88	8.793 ± 0.115	0.520
17584	F2III	IIIm	6726	3.56	-0.09	149	3.2	*1.26	6.18	1.91	9.112 ± 0.116	2.026
18557	A2m	V	7614	3.90	0.10	15	3.2	1.57	5.74	1.94	8.958 ± 0.052	1.267
21912	A3m	SB1O	8327	4.31	0.00	91	3.3	2.30	6.15	1.80	7.089 ± 4.000	0.026
23281	A3m	-	7689	4.20	-0.02	81	3.2	2.42	6.12	1.68	8.797 ± 0.287	0.199
24141	A5m	-	8070	4.22	0.35	54	3.3	2.21	6.38	1.78	8.633 ± 0.405	0.217
36484	A2m	SB	8711	4.27	0.00	35	3.2	1.90	5.82	1.93	8.312 ± 0.674	0.122
40062	A5m	-	7030	3.68	0.39	40	2.6	1.32	5.69	2.02	9.001 ± 0.076	2.110
42954	A5m	SB	7384	3.70	0.17	47	3.0	1.10	5.90	2.11	8.934 ± 0.074	2.087
44691	A3m	SB1O	7581	3.76	0.15	21	3.2	1.13	5.90	2.12	8.911 ± 0.064	1.897
60652	A5m	-	7647	3.86	0.44	63	3.2	1.40	6.15	2.01	8.935 ± 0.057	1.455
63589	A2m	V	8122	4.25	0.00	35	3.4	2.24	5.85	1.78	8.531 ± 0.603	0.161
67317	A1m	-	7165	4.18	0.43	35	2.7	2.77	5.42	1.55	8.989 ± 0.229	0.144
71297	A5m	-	7712	4.06	-0.03	13	3.2	1.97	6.29	1.81	8.935 ± 0.060	0.698
74190	A5m	-	7944	3.84	-0.22	58	3.3	1.13	6.28	2.13	8.868 ± 0.053	1.568
83886	A5m	-	8638	4.18	0.00	100	3.2	1.69	6.27	1.98	8.613 ± 0.220	0.375
84607	F4III	IIIm	7050	3.79	0.09	120	3.0	*1.66	6.46	1.89	9.052 ± 0.078	1.642
88295	(A0)	normal	8594	4.13	0.00	120	3.3	*1.58	6.36	2.01	8.683 ± 0.129	0.515
110326	A3m	SBO	7076	4.04	-0.26	65	2.6	2.42	5.54	1.63	9.116 ± 0.060	0.592
135774	A6m	V	6917	3.80	0.42	35	3.0	1.79	5.78	1.84	9.091 ± 0.078	1.579
136403	A2m	SBO	7670	4.01	0.17	20	3.2	1.87	5.81	1.84	8.955 ± 0.047	0.844
150557	F2III-IV	normal	6849	3.85	-0.18	95	2.7	*2.02	6.20	1.75	9.134 ± 0.068	1.323
169885	A3m	-	8050	3.91	0.03	60	3.4	1.26	6.11	2.08	8.864 ± 0.042	1.306
183262	A5m	-	7055	4.06	0.21	73	2.6	2.50	5.90	1.61	9.124 ± 0.065	0.499
190401	A7m	-	6877	3.81	0.25	40	2.8	1.84	5.86	1.82	9.104 ± 0.077	1.548
193472	A5m	SB2	7123	3.72	0.23	93	2.7	1.38	5.68	1.99	9.010 ± 0.076	1.907
213534	A5m	SBO	7632	3.74	-0.31	48	2.7	1.05	6.22	2.15	8.894 ± 0.064	1.968
221675	A2m	-	7223	3.84	0.53	70	2.8	1.67	5.76	1.89	9.031 ± 0.068	1.472
223461	A2m	-	7879	3.91	0.11	48	3.3	1.38	5.95	2.03	8.899 ± 0.044	1.282

the parallax is small, in general around 7%, so the error on the absolute magnitude is on average 0.15 mag.

As is well known, Am stars are often members of tight binaries, so we have to correct M_v for the flux of the companion. For this, we apply the following correction:

- For SB2 systems, we compute $\frac{M_1}{M_2} = \frac{K_2}{K_1}$ and with the mass-luminosity relation we obtain $\Delta m^* = m_1 - m_{1+2} = 2.5\log(1+10^{-\frac{m_1-m_2}{2.5}})$.
- For SB1 systems, $\Delta m^* = 0.2$ is assumed, which corresponds to a difference of 1.75 magnitudes between the components.
- If the star has a variable radial velocity according to the BSC or the catalogue of Renson et al. (1991), $\Delta m^* = 0.2$ mag is also assumed.
- If the star is only suspected of having a variable radial velocity according to the BSC ("V?" remark), no change is made.

Indications about multiplicity and variability are given in the column "Rem." of Tables 1 and 2. Except for HD 193472 which is an SB2, all stars are marked SB1, V or V? or have no remark.

We also compute a correction for visual binaries with angular separation less than 5 arcsec. This correction is applied only to HD 42954 which has a companion of the same magnitude at 0.5 arcsec, and to HD 67317 which has a faint neighbour at 1.4 arcsec.

The final HR diagram, where these corrections are taken into account, is presented in Fig. 3. Stars represented by black circles are those measured at OHP, those represented by black triangles are from Guthrie (1987). We have also plotted the two metallic giant F stars (open circles) and one normal star (open triangle). The size of each point depends linearly on the logarithmic calcium abundance. There is a striking deficiency of young Am stars with masses larger than 2 M$_\odot$.

4.1. Behaviour of Ca abundance with $\log t$

The Barcelona group (Asiain et al. 1997) has kindly transmitted to us a code which interpolates the age $\log t$ and mass of a star from its effective temperature and surface gravity, in evolutionary tracks from various authors including Schaller et al. (1992). As a first step, $\log g$ was computed from the absolute

Table 2. Parameters of age, masse, temperature and absolute magnitude for the stars of Guthrie (1987).

HR	HD	Rem.	$T_{\rm eff}$ [K]	M_v	$\log(\frac{N_{\rm Ca}}{N_{\rm H}})+12$	M [$M_\odot$]	log(t)	D_{1000}
178	3883	-	7279	0.30	6.11	2.34	8.851 ± 0.114	3.011
290	6116	-	7964	0.84	6.29	2.25	8.831 ± 0.062	1.976
418	8801	-	7222	2.69	6.13	1.57	8.988 ± 0.193	0.192
540	11408	-	8051	2.11	6.26	1.80	8.736 ± 0.240	0.325
976	20210	SBO	7509	2.32	5.50	1.70	8.951 ± 0.111	0.427
984	20320	SBO	7530	2.17	6.01	1.74	8.970 ± 0.073	0.594
1248	25425	V?	8059	0.41	6.05	2.45	8.762 ± 0.072	2.522
1368	27628	SB1O	7086	2.82	5.99	1.53	9.023 ± 0.215	0.146
1414	28355	-	7761	1.56	6.30	1.95	8.933 ± 0.046	1.152
1428	28546	V?	7468	2.24	6.31	1.71	8.982 ± 0.077	0.561
1511	30121	-	7636	1.81	5.91	1.86	8.964 ± 0.043	0.951
1519	30210	SB1?	7960	0.99	6.00	2.19	8.851 ± 0.172	1.755
1528	30453	SB1O	7413	0.98	6.29	2.17	8.909 ± 0.074	2.248
1627	32428	-	7246	1.24	5.78	2.05	8.972 ± 0.075	2.000
1670	33204	-	7207	2.24	6.16	1.70	9.070 ± 0.053	0.738
1672	33254	SBO	7553	1.97	5.70	1.80	8.983 ± 0.048	0.819
1689	33641	V	7868	1.53	6.22	1.97	8.909 ± 0.043	1.100
2566	50643	-	8042	0.39	6.30	2.46	8.761 ± 0.072	2.558
3320	71267	-	7757	0.91	6.24	2.21	8.862 ± 0.072	2.046
3354	72037	-	7814	2.04	5.78	1.80	8.887 ± 0.098	0.550
3619	78209	-	7281	2.13	5.78	1.73	9.051 ± 0.045	0.831
3655	79193	SBO	7556	1.71	5.99	1.89	8.981 ± 0.047	1.128
3988	88182	-	7945	1.74	6.29	1.90	8.886 ± 0.053	0.800
4021	88849	-	7074	1.81	6.14	1.83	9.072 ± 0.067	1.418
4237	93903	SB1O	7759	0.75	6.14	2.28	8.844 ± 0.073	2.271
4286	95256	-	7985	1.68	5.80	1.93	8.880 ± 0.050	0.837
4424	99859	-	8011	2.13	6.19	1.79	8.750 ± 0.234	0.326
4454	100518	-	7901	1.26	5.81	2.07	8.886 ± 0.049	1.427
4535	102660	-	7329	2.07	5.77	1.76	9.039 ± 0.045	0.871
4543	102910	-	7358	2.66	6.04	1.60	8.902 ± 0.277	0.152
4650	106251	-	7448	2.37	5.87	1.68	8.969 ± 0.110	0.406
4750	108642	SB1O	7884	1.67	5.90	1.92	8.905 ± 0.044	1.170
4751	108651	SBO	7782	2.34	5.90	1.71	8.780 ± 0.276	0.243
4847	110951	SBO	7036	1.05	5.92	2.12	8.960 ± 0.115	2.466
4866	111421	-	7727	0.49	6.45	2.39	8.813 ± 0.075	2.648
5045	116303	-	7366	0.60	6.05	2.20	8.929 ± 0.109	2.839
5405	126661	-	7378	0.68	6.38	2.16	8.950 ± 0.108	2.283
5752	138213	SBO	8369	0.52	6.28	2.41	8.747 ± 0.061	2.096
5845	140232	-	7844	2.17	5.91	1.77	8.829 ± 0.166	0.392
6555	159560	SBO	7321	2.63	5.78	1.60	8.947 ± 0.211	0.197
6813	166960	V	7265	1.88	5.86	1.82	9.046 ± 0.052	1.156
7019	172741	-	7438	0.52	6.27	2.24	8.908 ± 0.109	2.445
7056	173648	SB1O	7748	1.17	6.19	2.10	8.898 ± 0.058	1.679
7833	195217	-	7581	2.21	6.01	1.73	8.944 ± 0.096	0.514
7990	198743	SBO	7018	1.54	5.76	1.93	9.035 ± 0.089	1.832
8210	204188	SBO	7668	2.76	6.45	1.63	7.283 ± 4.000	0.008
8410	209625	SB1O	7583	1.24	6.02	2.07	8.925 ± 0.061	1.742
8970	222377	-	7749	2.16	5.93	1.76	8.884 ± 0.122	0.459
9025	223461	-	7879	1.39	6.26	2.02	8.900 ± 0.044	1.351

magnitude, assuming an inital mass of 1 $M_\odot$. Then $\log g$ was determined by the absolute magnitude and the mass given in the first interpolation. This iterative process was stopped as soon as the mass converged to $|(\frac{M}{M_\odot})_{i-1} - (\frac{M}{M_\odot})_i| \leq 10^{-3}$. The number of iterations seldom exceeded 10. The values of $\log t$ with its internal error and of the mass are given in Tables 1 and 2.

When a star is near the ZAMS, the uncertainty on $\log t$ increases dramatically, because there is a superposition of isochrones in this region. Only HD 21912, HD 36484, HD 63589 and HD 204188 are concerned by this problem. For them, the error on $\log t$ is larger than 0.5.

Fig. 4 shows the behaviour of $\log(\frac{N_{\rm Ca}}{N_{\rm H}})+12$ with $\log t$. The age of Am stars spreads between 8.6 and 9.15 with a clear de-

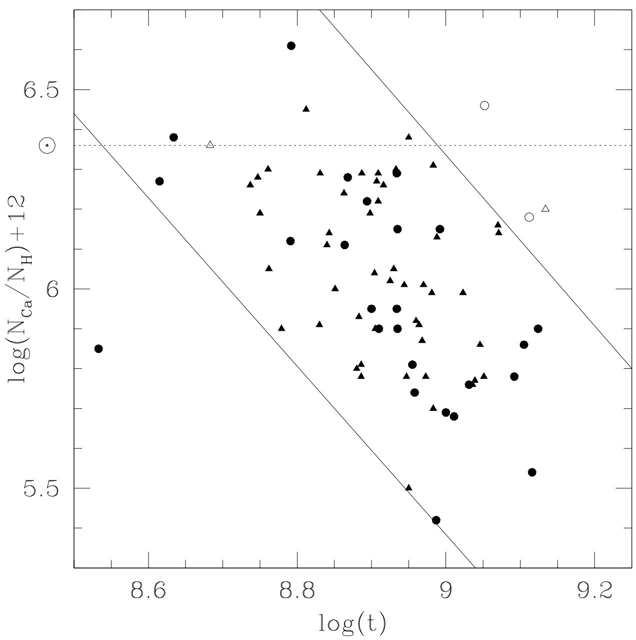

Fig. 4. Calcium abundance as a function of log t. See Fig. 3 for the key to symbols.

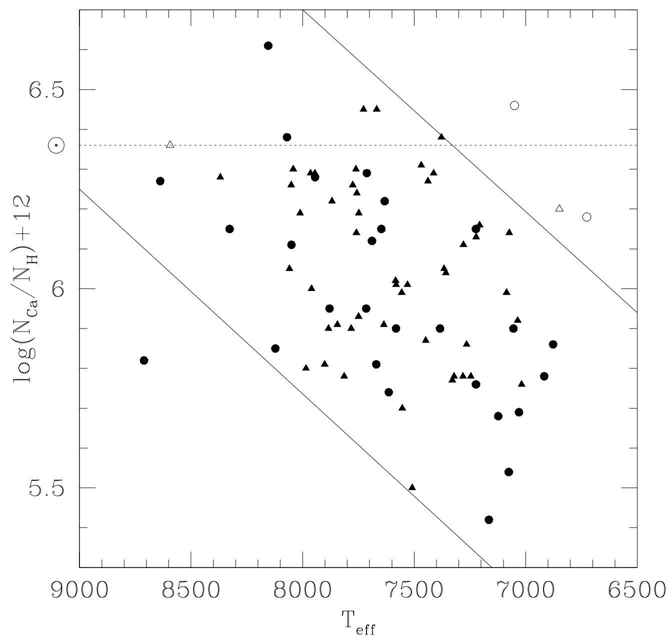

Fig. 5. Calcium abundance as a function of $T_{\rm eff}$. See Fig. 3 for the key to symbols.

ficiency of Am stars in the lower left part of the diagram. It means that A and F stars are really deficient in calcium only after $\log t \approx 8.8$. In order to test the significance of this result, a 2×2 contingency table was built, using a separation at $\log t = 8.875$ and $\log(\frac{N_{\rm Ca}}{N_{\rm H}}) + 12 = 5.88$. We get $\chi^2 = 9.88$ while the value for the 99.5% confidence level is 7.88. This dependence between Ca abundance and age seems to confirm qualitatively Alecian's theory, which predicts a calcium deficiency for slowly rotating A and F stars from $\log t = 8$ on, that is 0.6-0.8 dex earlier than our observations suggest. However, this relation betrays a correlation between Ca abundance and effective temperature (Fig. 5): since cooler stars are also older, one will necessarily observes a relation between Ca abundance and age.

We have made some simulations to test the interdependence between age, effective temperature and Ca abundance. First, one has synthesised a population of Am stars with masses and ages distributed at random (assuming a Salpeter IMF combined with the relative mass distribution of North 1993); the age distribution was not uniform, but modified so as to mimic the observed one. By interpolation in evolutionary tracks of Schaller et al. (1993), we obtain both effective temperatures and absolute magnitudes. Finally, we determine $\log t$ as before and then can plot $\log(\frac{N_{\rm Ca}}{N_{\rm H}}) + 12$ vs $\log t$ assuming a relation between effective temperature and Ca abundance. If we impose the observed relation between $T_{\rm eff}$ and Ca abundance given in Fig. 5, we recover the relation between $\log t$ and $\log(\frac{N_{\rm Ca}}{N_{\rm H}}) + 12$ shown in Fig. 4. The left part of Fig. 6 illustrates this fact, the oblique lines being at the same positions as in Fig. 5 and 4. On the other hand, if we impose no relation between temperature and Ca abundance, there is no relation either between age and Ca abundance (Fig. 6, right part). These simulations show that temperature effects almost perfectly mimic age effects and vice-versa, at least when all stars are considered together. Even if one considers only stars distributed along an evolutionary path (all having the same mass), it is not possible to discuss age effects independently of $T_{\rm eff}$ effects, since both parameters are intimately related. When a star follows an evolutionary track, the effective temperature decreases and the age $\log t$ of course increases; if the correlation between $T_{\rm eff}$ and Ca abundance found above holds, then one may expect that an evolving Am star will become more and more Ca-deficient. This point is examined in more details in the next subsection.

Even if the effect of age on Ca abundance can not be isolated from that of $T_{\rm eff}$, it is interesting to consider the histogram of ages. As seen in Fig. 7, most of our field Am stars are older than $\log t \approx 8.8$ (in the histogram, we do not take into account the four stars having a large error on $\log t$). Although our sample should be considered as biased because it was defined with the purpose of populating a few evolutionary tracks as uniformly as possible, Guthrie's sample is not biased towards young or old objects, and it constitutes two thirds of the whole sample. Therefore, we think the distribution of Fig. 7 shows a real lack of young Am stars. This fact is coherent with the deficiency of Am stars in young clusters.

4.2. Behaviour of Ca abundance along an evolutionary track

In order to know how the Ca abundance tends to vary with evolution for stars *of a given mass*, we define the D_{1000} parameter as the difference between the present effective temperature of the star and the one it had on the ZAMS, divided by 1000 just

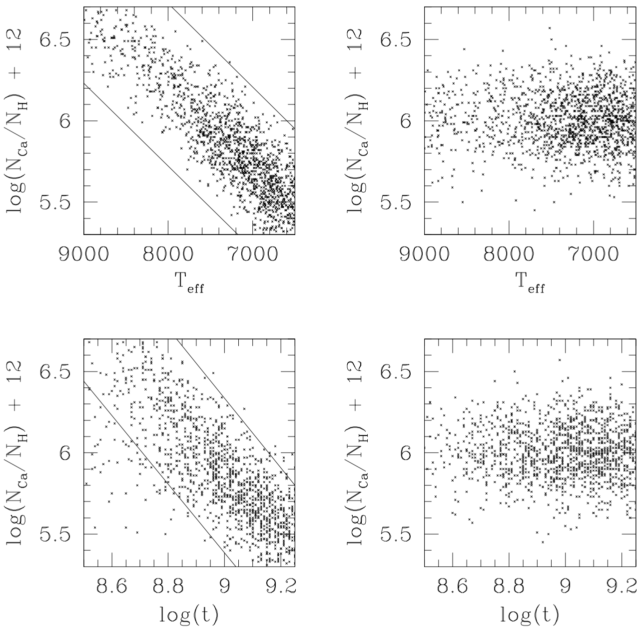

Fig. 6. Diagram of synthesised Am stars. The two leftmost figures reproduce exactly what is observed. If there is no relation between Ca abundance and $T_{\rm eff}$, there is no relation either between age and Ca abundance, as shown in both rightmost diagrams. Temperature effects closely mimic age effects and vice versa, so these two quantities are not independent.

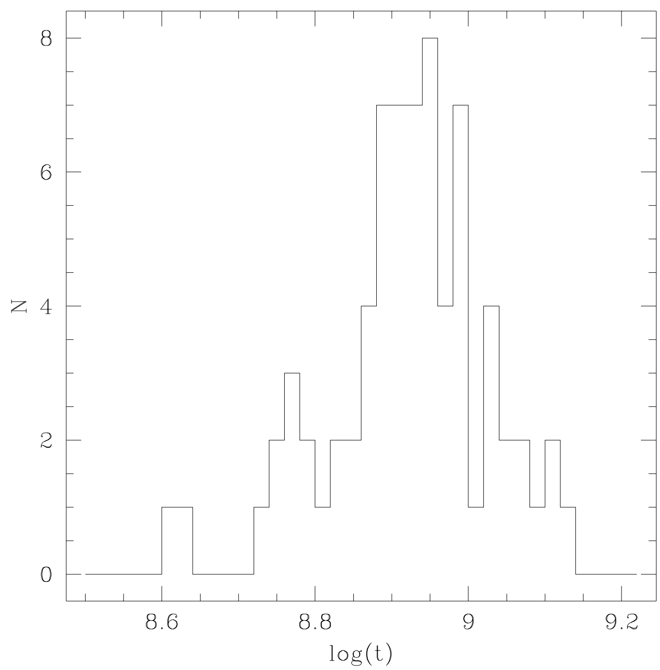

Fig. 7. Histogram of $\log t$ for the Am stars considered in this paper.

to have a number close to unity. In other words, this parameter represents the "horizontal" component of the distance covered by the star in the HR diagram along an evolutionary track:

$$D_{1000} = \frac{T_{\rm eff} - T_{\rm eff}({\rm ZAMS})}{1000} \quad (1)$$

This parameter therefore measures a kind of age, i.e. the time which has expired since the star left the zero-age main sequence, although it is of course not on a linear scale.

D_{1000} is correlated with the depth of the convective zone and consequently with Ca abundance, according to the scenario of Berthet (1992). To show this dependence, we have defined four mass ranges: $1.5 \leq M/{\rm M}_\odot \leq 1.7$, $1.7 \leq M/{\rm M}_\odot \leq 1.9$, $1.9 \leq M/{\rm M}_\odot \leq 2.1$ and $M/{\rm M}_\odot \geq 2.1$. The Ca abundance was then plotted against D_{1000} for each of these ranges (Fig. 8). If Berthet's (1992) idea was right, we should see an increasing calcium abundance with increasing D_{1000} because at a constant mass, D_{1000} increases along a given evolutionary track. Fig. 8 shows that this is definitely not the case: there is no correlation between $\log(\frac{N_{\rm Ca}}{N_{\rm H}})$ and D_{1000}. In Figs. 8b and 8c, we rather see the reverse correlation, i.e. an increasing calcium deficiency with evolution. This rough correlation is in agreement with the preceding result: $T_{\rm eff}$ decreases with evolution and Ca gets more depleted.

If we superimpose Figs. 8a and 8d, a positive correlation appears between $\log(\frac{N_{\rm Ca}}{N_{\rm H}})$ and D_{1000}, which is due to a temperature effect but not to any evolution effects. Guthrie (1987) analysed the behaviour of $\log(\frac{N_{\rm Ca}}{N_{\rm H}})$ with $\delta c'_o$ (which is a photometric parameter in the Strömgren system similar to D_{1000}) without any distinction of mass or temperature, and Berthet (1992) did not take into account the effect of temperature either; this is probably the main reason for the difference between their result and ours.

5. Conclusion

We have analysed the dependence of Ca abundance with evolution in the atmosphere of Am stars. In this paper, we put forward the impossibility of isolating the dependence of Ca abundance on time alone, because when a star evolves, time is intimately related to temperature so that these two parameters cannot be discussed separately.

Cool and old Am stars are more Ca-deficient than hotter and younger ones. So, when an Am star evolves its Ca abundance probably decreases. But we can only guess that the physical cause for this is the decreasing temperature in the star's envelope just below the H I convective zone, which implies a decrease of the radiative acceleration applied to the Ca II ions. However, the parallel decrease of the surface gravity acts in the opposite sense and only detailed, time-dependent modelling such as Alecian's will allow a proper interpretation of the data.

The D_{1000} parameter, which measures the evolutionary state of a star, depends on both age and temperature. For constant mass, D_{1000} follows an evolutionary track and so measures directly the effect of evolution. We have shown that there is no positive correlation between D_{1000} and Ca abundance, contrary to the claims of Berthet (1992) and Guthrie (1987). There is rather a decrease of the calcium abundance as evolution proceeds. In their study, Berthet (1992) and Guthrie (1987) have mixed stars with different masses and temperatures, which prob-

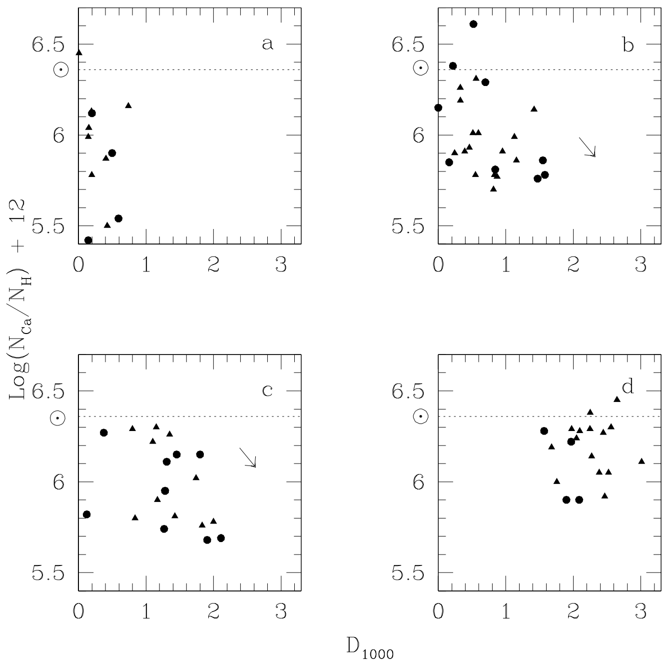

Fig. 8a–d. $\log(\frac{N_{\rm Ca}}{N_{\rm H}})$ + 12 as a function of D_{1000} for different range of mass; **a** 1.5 $\leq M/{\rm M}_\odot \leq$ 1.7, **b** 1.7 $\leq M/{\rm M}_\odot \leq$ 1.9, **c** 1.9 $\leq M/{\rm M}_\odot \leq$ 2.1, **d** $M/{\rm M}_\odot \geq$ 2.1. See Fig. 3 for the signification of symbols.

ably led them to a wrong conclusion, essentially due to a temperature effect.

Most ages of our field Am stars spread between $\log t$ = 8.6 and 9.2, which agrees well with the lack of Am stars in young open clusters (North 1993).

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