Astron. Astrophys. 318, 870–878 (1997)

ASTRONOMY AND ASTROPHYSICS

The Pleiades open cluster: abundances of Li, Al, Si, S, Fe, Ni, and Eu in normal A and Am stars*

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Received 15 April 1996 / Accepted 26 June 1996

Abstract. In the first of a series of papers on the A stars in open clusters, normal A and Am stars in the Pleiades were observed with the Canada-France-Hawaii telescope at high spectral resolution and high signal-to-noise ratios. Photospheric abundances have been determined for Li, Al, Si, S, Fe, Ni, and Eu from model atmosphere abundance analysis.

The A stars of the Pleiades are at the beginning of their Main Sequence evolution. At this stage, Li is clearly deficient in the Am stars compared with the normal A stars (-0.65 dex), and the abundance of Fe is the same for both stellar groups, twice its original solar value as given by the Pleiades F stars. These Fe results are unexpected since, firstly, normal A stars are thought to have normal abundances and, secondly, Am stars are classically said to be overabundant in Fe compared with normal A stars. The maximum Li abundance of the cluster is found in the normal A stars with log N (Li) = 3.55 $\pm$ 0.1 on the scale log N (H) = 12.0. These stars seem to have preserved their original Li better than any other cooler stars of the Pleiades cluster.

The behavior of Li in the slow-rotator Am stars versus the rapid-rotator normal A stars in the Pleiades is exactly comparable with that found in the "low v sin i" versus "high v sin i" stars with similar masses in the Orion association. Could it be that Li differentiation between Am and normal A stars takes place during their pre-Main-Sequence evolution?

The Li results in the Am stars challenge predictions from model envelopes coupling diffusion and evolution (plus mass loss) in non rotating stars since only strong underabundances are expected at the age of the Pleiades.

Key words: open clusters: Pleiades – stars: abundances – stars: rotation

1. Series context and objectives

This paper is the first in a series about the abundance of the trace light element Li for the normal A and Am stars in open clusters of different ages; the abundances of Al, Si, and S; the abundances of iron peak elements, Fe and Ni; and the abundance of the rare earth Eu. This paper is concerned with the normal A and Am stars of the Pleiades and defines our objectives.

In observing stars in clusters of different ages and studying their photospheric abundances, our objectives have two main aspects. The first is to understand **the origin and evolution of the anomalous abundances in the Am stars** better. These anomalies observed at the surfaces of Am stars (which are the slowly rotating A stars) are currently explained by microscopic diffusion just below the superficial convection zone. New detailed calculations (Richer & Michaud 1993) gave results on the time evolution of the internal distribution of elements in the envelopes of non-rotating population I A stars for the whole Main-Sequence lifetime of the stars. According to these models, surface anomalies are expected to change with time and the abundance evolution is expected to differ from one element to the next. Therefore, observed correlations between the abundances of a number of elements and ages would provide constraints on envelope models and information on the complex hydrodynamical processes at play. Studying a star, which is a member of a cluster, gives astronomers the opportunity to know its age and the time available for diffusion and other processes to act, but also information of its position inside the Main Sequence and its initial chemical composition (on the ZAMS). This composition may be known thanks to cluster members undergoing no chemical composition change in the surface abundances during their main sequence evolution: a priori, we can turn to cooler stars, F and G (except for Li) or normal A stars. The only comprehensive abundance studies of normal A and Am stars in clusters are those by Conti and coworkers in the 1960's and Smith in the early 1970's. The importance of such studies is renewed thanks to progress in observation techniques and data processing as well as in modeling. Conti & Strom (1968) studied the Pleiades, Conti (1965) and Conti et al. (1965) the Hyades, and Smith (1971) the UMa group, Coma, and the Hyades. This series will deal with the Pleiades, Coma, Praesepe, and the Hyades.

The second aspect of this work is to extend our knowledge of **Li abundances in clusters on the hot side of the Li dip** and

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* Based on observations collected at the Canada-France-Hawaii telescope (Hawaii)

to clarify the complex picture of Li abundances given by field A stars. For normal A and Am-Fm field stars, lithium abundances range from a maximum of log N (Li) ~ 3.8 down to ~ 2.0, which is not measurable, a range around 3.1 on the scale log N (H) = 12.00 (Burkhart & Coupry 1991). From now on, the meteoritic Li value log N (Li) = 3.3 is called the normal Li abundance. The dependence on temperature is not simple and the role of a weak evolution around the TAMS (terminal age main sequence) on the Li deficiencies is suggested. If one selects a uniform sample of stars by age, the parameter "time" is decoupled from the other stellar parameters. A more coherent picture will emerge as in cooler stars, more especially as with any Am (and even any normal A) star the stage of evolution is difficult to assign from luminosity class or photometric indices. Uniform age samples are easily supplied by open star clusters. Unlike cooler stars, A stars are believed to undergo no Li burning in their envelopes on the pre-Main-Sequence as well on the Main Sequence. A priori the presently observed Li abundance in the atmosphere of a normal A star is representative of the Li content of the cloud from which the protostar formed. Studying Li in the normal A stars of one cluster may be a good way to determine the Li abundance in the Galaxy at the time and place of the cluster's birth; then studying clusters of different ages could, in principle, give some information concerning the galactic evolution of Li abundances. Am stars are slow rotators and have some place in their envelope stable enough for particle processes to be efficiently at work: the presently observed Li abundances in their atmospheres are, thus, the combination of the Li content of their birth clouds and the outcome of particle processes undergone during the Main Sequence evolution. Some Li abundance results in clusters with the A stars have been already published. With some ten Am stars in two clusters of nearly the same age, Coma (Boesgaard 1987) and the Hyades (Burkhart & Coupry 1989), the Li abundance is constant and equal to about 3.0 within a large range of temperatures, but near 8000 K there is a real spread with over-, under-, and normal abundances. This series extends the sample of the observed stars of Coma and Hyades, and the cluster sample to Praesepe of the Hyades age and the Pleiades which are younger by one order of magnitude.

We have to consistently sort A stars into Am and normal A groups. The Am stars have strictly been those where Ca, relative to H, is underabundant, the normal A stars being those with Ca normal (or overabundant). It is evaluated for middle and late A, early F stars with the refined MK classification of Gray & Garrison, hereafter G&G, (1987, 1989a, and 1989b) and/or the line ratio Ca I - 6717/ Fe I - 6678 within our observed spectral range (see Burkhart & Coupry 1991 for details). In our study we will found some difficult sorting cases; we will deal with these on a case by case basis.

We expect mild abundance anomalies: up to now they have been found to be less than 1.0 dex from the solar value (or from the cosmic value for Li) and in general less than 0.5 dex. To be significant the abundances must be based on high signal-to-noise (S/N) and high-resolution spectra, made on homogeneous observational data and derived with a homogeneous method. The required spectra are now within reach for the nearest open clusters thanks to new detectors, modern spectrographs, and 4m-telescopes. All the spectroscopic data of this paper series have been obtained near 6700 Å at the Canada-France-Hawaii (CFH) 3.6m telescope and the f/7.4 coudé spectrograph camera equipped with a Reticon detector of 1872 diodes. This configuration used with the 830 lines mm^{-1} grating during two runs yields spectra covering 135 Å at a dispersion of 4.83 Å mm^{-1} with a resolving power about 35000. Some of the brightest stars have been observed with the 1800 lines mm^{-1} holographic grating during other runs: these spectra cover 55 Å at a dispersion of 1.97 Å mm^{-1} with a resolving power about 90000. Typical signal-to-noise ratios are 200 to 400 at the 2σ level.

Comparisons between these runs and both dispersion data sets were done with α CMi observed during each run. A general external data check can be done with this already well-observed star and/or lunar spectra secured to determine solar log gf values. The comparison, for example, of our equivalent widths for the solar spectrum observed at the CFH in 1992 with those of Rutten & Van der Zalm (1984) from the Sacramento Peak atlas of the full-disk solar spectrum (Beckers et al. 1976) is as follows. The least-squares fit with 16 lines yields:

$$\mathrm{W}_\lambda\,(\mathrm{CFH92}) = \underset{\pm 0.04}{0.99}\,\mathrm{W}_\lambda\,(\mathrm{Rutten}) + \underset{\pm 1.23}{0.86} \quad (m\text{Å}) \qquad (1)$$

This good agreement between both equivalent width scales supports the computed solar log gf values (see Coupry & Burkhart 1992). In these log gf computations, we adopt the solar photospheric abundances from a critical review (Anders & Grevesse 1989) except for Fe. Instead of the high value of log N (Fe)$_\odot$ = 7.67, on a scale with log N (H) = 12, obtained from low excitation Fe I lines, we adopt the meteoritic value of 7.51 according to recent analyses based on new accurate transition probabilities for higher excitation lines in Fe I and for Fe II lines (see, e.g., the articles in 1995 by Blackwell et al. and Holweger et al.). When merging or comparing iron abundances in clusters from different sources, we must bring values onto a common scale. The new log gf values are given in Table 2 of this paper with the laboratory log gf values of the Li lines.

In Am stars the rare earths are generally clearly enhanced in comparison with normal stars. Unfortunately the solar log gf determination of the Eu II λ 6645.13 line cannot be computed in a very satisfying manner. The line is flanked at λ 6645.35 by a red line that is easily seen in solar and Procyon atlases (Beckers et al.1976; Griffin & Griffin 1979), and blended in our spectra. This satellite line could not be identified with any known atomic or molecular line by Grevesse & Sauval in 1993. A solar Kurucz synthetic spectrum of the region computed by Castelli (1994) tentatively suggests the existence at λ 6645.36 of a Fe I line. Nevertheless, the fit is very bad and another unknown line(s) could be present. The too large log gf value that we find when all the λ 6645 feature is attributed to europium is equal to 0.35. It is consistent with the relative size of the Eu line with unknown line(s) as seen in a solar spectrum and the accurate absolute value of 0.204 for the Eu line alone (Biémont et al. 1982). The effects of the hyperfine structure of that very weak Eu II line are ignored, as Biémont et al. (1982) do it for their solar abundance estimate of Eu from lines which do not lie on the flat portion of the curve of growth (Hartoog et al. 1974), more especially as no hyperfine structure data are available for the λ 6645.13 line. Since we know nothing about the nature and characteristics of the satellite line(or lines), we cannot estimate its behavior from the Sun to the A region, the important parameters being, a priori, the gradient of temperature and abundances with a special mention of possible high Am overabundances of rare earths other than Eu. Taking into account the differential character of this study, and the central wavelength and profile of the 6645 feature involving europium as the main component in A spectra, we are however confident for the europium abundance on an error less than 0.2 dex in consequence of presence of satellite line(s).

The data reduction was carried out with codes written by M.Spite (1989); abundances were derived using model atmospheres (Kurucz 1979a, b) with temperatures derived from uvby, β photometry (Moon 1985; Moon & Dworetsky 1985). (See Burkhart & Coupry, 1991, and references therein for a description of the basic data, the reduction procedure, and the abundance determination). Owing to the uvby, β measurements, a typical error in temperature is $\pm$ 100° K, which corresponds to an error about $\pm$ 0.06 or 0.07 dex in the case of Li, Al, Si, Fe; in stars in open clusters the photometric indicators of temperatures can be measured with a higher degree of internal consistency than in field stars. The values of temperatures determined for Am stars are not significantly affected by their metallicism (Smalley & Dworetsky 1993). These homogeneous data processed and converted into abundances with a single chain will thus warrant any comparison between Am versus normal A stars and between different clusters. This chain is what we use in our studies of the Hyades (1989) and field stars (1991), promoting direct comparisons. On the other hand, the adopted photometric calibration of effective temperatures, T_{eff}, of Moon & Dworetsky (1985) shows excellent agreement with effective temperatures re-determined by Napiwotzki et al. (1993), and a re-evaluation of the 1985 calibration by Dworetsky & Smalley (1996) yields remarkably small differences.

2. Program stars, observations, and data reduction

The 13 observed Pleiades stars are shown in the cluster color-magnitude diagram limited to the hottest part (Fig. 1). They are composed of all the stars listed Am in 1988 & 1990 by Renson (seven in number) and the sharp-lined normal A stars (six stars with presumably v sin i less than about 60 km s^{-1}).

Some stellar characteristics and observation data are collected in Table 1. In column 1, 4 names are not bold-faced but italic type; the corresponding stars are not studied later and we give here some information about them. The hot star, HD 23387, has only one blended line in its spectrum. The three others are very likely spectroscopic binaries with 2-line systems (SB2). The first one, HD 23642, is already known as SB2; being a hot star, its spectrum is unworkable. The last two would be new SB2 if confirmed. We detected the Li feature in HD 23791 just as

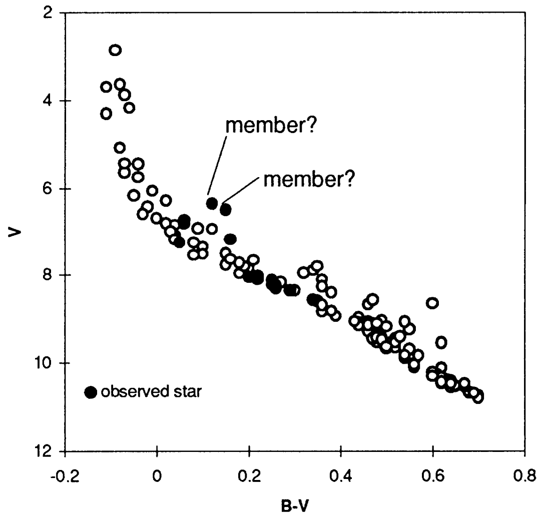

Fig. 1. Color - magnitude diagram for the Pleiades cluster showing observed stars. The 2 observed uncertain members are reported. The UVB photometry is that of Johnson & Mitchell (1958)

Pilachowski et al. (1987)did it; they have given an upper limit of 20 mÅ to the equivalent width that must be taken with caution, since the likely SB2 character had been ignored. The Li feature of the last SB2, HD 23964, is strong in one line-system. It may be connected either with a Li overabundance in the corresponding component (as it had been already found in some SB2 systems) or with its classification as B9.5p (Abt and Levato 1978) and the curious unidentified strong feature observed in a few Ap stars by Gerbaldi and Faraggiana (1991).

One problem in observing stars in any cluster is ascertaining their membership. From their proper motions and spectral types (or colors), memberships of 11 observed stars have been confirmed, those of the last two, HD 22615 and HD 24368, rejected and quoted "uncertain member" (Trumpler 1921). Except these two stars outlying away from the cluster center by a few degrees and reported "member?" in Fig. 1, the observed stars all lie in the main sequence of the cluster. None of them belongs to the class of photometric binaries (well above the ZAMS) even if it is actually a spectroscopic binary (SB), eventually SB2. Am stars are not distinguished from normal stars by their position in Fig. 1. Souchay (1994) confirms rejection of one of the two uncertain members, HD 24368, from a new proper motion study of the cluster.

The equivalent widths are given in Table 2. Each of the Al, Li, Ca, and S lines is the main line of a blend with a weak Fe line; the equivalent width value found in Table 2 is, then, that of the entire blend and "bd" is put for the satellite line. For Eu, the equivalent width value is that of the blend. The comparisons with previously published data are sparse. For HD 23607, Pilachowski et al. (1987) reported a Li equivalent width of 32 mÅ to be compared with our blend value of 25 mÅ. For HD 23194, Hobbs & Duncan (1987) have not detected the Li and Ca blends and obtained upper limits of 9 mÅ in each feature, in contrast with our equivalent widths of 11 and 36 mÅ respectively. This

Table 1. Log book

	Sp type G&G (Renson)	Ca/Fe	V	Exp time (mn)	JJ -2440000	Remarks
HD 22615	A3 IV (A3-F0m)	Am	6.5	23	7890.78	uncertain member
HD 23156	A7 V	nl	8.2	46 90	7890.82 8644.76	δ Scuti; P=34mn
HD 23194	A5 V (A4-A7m?)	nl	8.05	120	7892.78	SB
HD 23325	(A2-A8m)	Am	8.6	120	8647.85	X rays : detected
HD 23387			7.2	90	8645.84	*unmeasured spectrum* SB; VB
HD 23607	(A4-F2m)	nl?	8.3	120	7892.87	δ Scuti
HD 23610		Am	8.1	120	8646.74	
HD 23631	A0 mA1Va (A0-A3m)	hot star	7.3	70 105	7891.82 8645.74	SB1; P=7.3d X rays : detected
HD 23642	(A0V+Am)	hot star	6.8	60	8646.81	SB2; P=2.5d *unmeasured spectrum*
HD 23791	A9 V^{+}		8.4	150	8647.75	SB2 (line profiles in this work) : 2 Am spectra Li line : present
HD 23924		nl	8.1	90	8644.83	
HD 23964		hot star	6.7	75 30	7891.88 8645.79	SB2 (this work) : 1 Am? and 1 nl spectra; P=16.7d Li : surabundant in the nl star
HD 24368	(A0m?)	hot star	6.3	39	7891.77	X rays : detected uncertain member

Table 2. Equivalent widths (mA)

	λ		Mult.	χ	log gf	HD 22615	HD 23156	HD 23194	HD 23325	HD 23607	HD 23610	HD 23631	HD 23924	HD 24368
Ni I	6 643.638		43	1.68	-2.10	20	10			11	20		20	1.5
Eu II	6 645.127	HF	8	1.38	0.35	5	<7			<4			6	1.5
Fe I	6 677.997		268	2.69	-1.67	62	68	36	87	70	62	8	72	13
Al I	6 696.032		5	3.14	-1.62	10	12			8	4 ?		12	
Fe I	6 696.322		1255	4.83	-1.60	bd	bd			bd	bd		bd	
Al I	6 698.669		5	3.14	-1.91								7	
Fe I	6 699.136		1228	4.59	-2.17								bd	
Fe I	6 705.105		1197	4.61	-1.20	9	12		20.5		12		15	2
Fe I	6 707.449				-2.20	bd	bd	bd	bd	bd	bd		bd	
Li I	6 707.760		1	0.00	0.00	<2	29	11	18	25	7	<2	30	<1.5
Li I	6 707.980		1	0.00	-0.30	bd	bd	bd	bd	bd	bd	bd	bd	bd
Fe I	6 717.527		1194	4.61		bd	bd	bd	bd	bd	bd		bd	
Ca I	6 717.687		32	2.71		28	63	36	49	53	25	3	62	5.5
Si I	6 721.844		38	5.86	-1.20	13	21	14		16	6		22	1.5
Fe I	6 726.673		1197	4.61	-1.18	8	13			10	8		11	
Fe I	6 733.153		1195	4.64	-1.53					4.5				
Fe I	6 750.164		111	2.42	-2.78					12	6			
Fe I	6 752.716		1195	4.64	-1.33	6 or >				6.5				
Fe Ip	6 756.568		1120	4.29	-2.61	bd	bd	bd	bd	bd	bd		bd	
S I	6 757.195	F	8	7.87	-0.21	61	59	37	43 ?	44	39	12	91	18

poor agreement is likely because of much higher signal-to-noise ratios of our spectra than available to previous researches.

3. Analysis and results

Table 3 sums up our Pleiades abundance results. In col. 2 the normal A or Am character is given from the process of Part 1. HD 23607 has not been classified by Gray & Garrison; its Ca/Fe line ratio, equal to 0.75, is on the verge of normal A group just as the Sc/Sr line ratio in Conti & Strom (1968). Connecting this with the abundance results of Conti & Strom (1968), HD 23607 has been considered as normal star in this work. The second difficult sorting has been that of HD 22615. From Gray & Garrison (1989b), it is a normal star, A3 IV, at variance with its weak (0.44) Ca/Fe line ratio denoting an Am star just as its weak Sc/Sr line ratio in Conti & Strom (1968). Joining this to the MK classification of A3m: by Cowley et al. (1969), we suppose HD 22615 to be an Am star, ignoring the G&G classification. This choice will anyway not weigh in the conclusions drawn for the Pleiades cluster; the main point will be the uncertain membership of this star.

In col. 3 the temperatures derived from uvby,β photometry are given. In the Pleiades region the patchy distribution of the many, small-sized dust clouds results in differential reddening for stars in different regions of the cluster; the uneven reddening has been found, nevertheless, to be essentially uniform (Soderblom et al. 1993a) except for a small region in the south-west part of the cluster where an isolated CO cloud appears. Any possible variable reddening over the cluster is taken into account in the program of Moon through the excess of (b-y), E(b-y), for each star. HD 24368 has no uvby,β measurements and cannot have its temperature determined in the same scale as the other

Table 3. Parameters of the models and abundances of the Pleiades stars

		Teff °K	vt km/s	log N (Li)	log N (Al)	log N (Si)	log N (S)	log N (Ca)	log N (Fe)	log N (Ni)	log N (Eu)
HD 22615	Am member?	8400	>5	< 2.4	6.8	7.8	7.4		7.9	6.8	1.15
HD 23156	A	8070	5	3.6	6.6	7.8	7.3		7.9	6.2	< 1.1
HD 23194	A	8430	?	3.4		7.8	7.15		7.7		
HD 23325	Am	7670	3	3			7 ?		7.8		
HD 23607	A	8100	5	3.55	6.4	7.7	7.1		7.8	6.25	< 0.9
HD 23610	Am	7950	3	2.8			7.05		7.8	6.5	
HD 23631	hot (Am)	9460					7.3	6.5	7.9		
HD 23924	A	8180	5	3.65	6.7	7.9	7.6		7.85	6.5	1.05

stars. It has been measured in the Geneva photometry but there is no way to deredden the star for certain without knowing its E(b-y). We have tried to take the mean of the E(b-y) found for the other stars of this article; it leads to a temperature of 8750 K, very different from that, 9500 K, found by Conti et al. (1968) in their abundance analysis. So, we drop this star in Table 3, more especially as its membership presently is really doubtful. We note that a middle temperature of about 9100K involves similar abundances to those of Pleiades Am stars and of course the Geneva or Conti temperature yields dissimilar abundances.

The microturbulent velocity, v_t, in col. 4, is obtained as a pure fitting parameter to obtain equal Fe abundances from lines of different equivalent widths (the strong line at 6678 Å versus the weakest lines). Coupry & Burkhart (1992) noted the feasibility of finding a microturbulence on the basis of a limited wavelength range thanks to high quality spectra and the ease in setting the continuum of the Li region. In the Pleiades, the two Am stars follow the trend of v_t with temperature shown in Coupry & Burkhart (1992); on the contrary, the microturbulence is significantly larger for the A stars (and the uncertain Am member, HD 22615). Microturbulence values affect abundances determined from only strong lines; therefore the only abundances of S for the three stars, HD 22615, HD23156, and HD 23924, would be higher if their actual microturbulence were to be reduced.

In the end, after removing difficult spectra, uncertain measurements, or uncertain cluster membership, the abundance results (Table 3 and Fig. 2) are of good quality, homogeneous, but few. We will discuss the elements with most results, Li, S, and Fe; the other elements, as also the hot Am star, will be addressed in the clusters all together in a forthcoming paper of this series. In the Pleiades:

- The two Am stars have very much alike abundances in Li, S, and Fe. The four normal A stars behave in like manner for Li, Si, S, and Fe, except one star richer in S.
- The atmospheres of normal A stars, compared with Am stars, have more Li (+ 0.65 dex) and, according to our Am definition itself, more Ca.
- The atmospheres of normal A and Am stars have the same Fe content: an intrinsic dispersion less than 0.1 dex is consistent with observational error alone.
- S may be marginally overabundant in normal A stellar atmospheres in comparison with those of Am (+ 0.25 dex).

We discard the possibility to abundances in Am stars to be significantly affected by metallicism because of an error in temperature (according to Smalley & Dworetsky 1993) or because of the use of solar abundance models for a slightly abnormal star like an Am star (which is currently assumed). We, thus, conclude that at the age of the Pleiades, about 0.1 Gyears, when A stars are at the beginning of life on the Main Sequence, Am stars, compared with normal A stars with same initial chemical composition and comparable temperature, convincingly have the same photospheric content of Fe and less Li (and Ca).

Our abundance results in A Pleiades stars are to be compared with those in cooler Pleiades stars and/or the Sun.

In the case of Fe, the four normal A and two Am stars are found to be equally overabundant compared with the Sun (+ 0.3 dex). If we turn to the accurate results for F dwarfs (Boesgaard 1989; Boesgaard & Friel 1990), the mean of [Fe/H], equal to log $(Fe/H)_\star$ - log $(Fe/H)_\odot$, has been found to be resp. + 0.022 $\pm$ 0.06 and - 0.034 $\pm$ 0.024, i. e., essentially a solar Fe abundance with an extremely small intrinsic dispersion. For these F stars, the model atmospheres used are those of Kurucz (1979a,b), i.e. the same grid as ours, and the temperature scale is primarily that of Saxner & Hammarbäck (1985) whose empirical calibration of (b-y) and H_β -index is found by Smalley & Dworetsky (1995) to yield values of T_{eff} in good overall agreement with those derived from grids of Moon & Dworetsky (1985) which are used in this paper series. An important decrease of the A temperature alone seems, thus, absolutely excluded (for example, + 0.3 dex in abundance corresponds to a decrease by about 400 K). So in their atmospheres, both normal A and Am Pleiades stars are equally overabundant in Fe compared with F Pleiades stars, with the only limitation of possible trends in temperature and/or inhomogeneities in the model grid of Kurucz (1979) due to change in the envelope physics in consideration of the several thousand-degree range, 8500 to 6000 K, involved.

In the case of Li, we turn to a most extensive study in Pleiades F, G, and K dwarfs by Soderblom et al. (1993b). Fig. 3, a partial reproduction of their Fig. 9b, shows the Li-temperature profile of all our observed stars with theirs, T_{eff} less than 5500 K and/or upper limits excluded. The maximum Li abundance is found in the four normal A stars. The scatter is about 0.1 dex, consistent with our observational uncertainties alone, due to temperature determination and the unique weak Li line, which is difficult to measure, principally in broad-lined stars. The mean of log N(Li), 3.55, is higher by about + 0.25 dex than those for the three cooler stars around 6900 K in Soderblom et al.. This difference seems significant to us since the temperature scale of Soderblom et al. is in good agreement with that of Boesgaard & Friel (1990) for F dwarfs; we are therefore brought back to the same case as for Fe. The Li abundance in Pleiades normal A stars is, even, more significantly higher than in Pleiades late -F to early G stars in the range 5950 to 6350 K, constituting the "Li peak" in clusters (Boesgaard 1991), since the difference is 0.45 dex.

4. Discussion and conclusion

The abundance of iron leads to two unexpected results in the Pleiades. The first striking result is the same abundance for Am and normal A stars, when Am stars are classically said to be overabundant in Fe compared with normal stars. The second striking result is the Fe overabundance of the normal A stars, when they are thought to have preserved in their atmosphere their initial chemical composition, that is solar iron abundance as F Pleiades stars.

We recall specifications of this work; they divide in four chief groups, and have never been joined together in previous studies, which may be the origin of these new results:
1- Stars are members of one cluster. They are of the same age and initial chemical composition.
2- Am stars are compared with middle and late normal A stars of nearly the same temperature.
3- At the age of the Pleiades, the A stars begin their life on the Main Sequence (see Fig. 1 for an illustration).
4- Accurate and homogeneous abundances have been determined from high signal-to-noise and high-resolution spectra processed in a unique analysis technique. In particular, if uncertainties in the absolute temperature scale may shift the abundances of all normal A and Am stars in a similar way, the relative T_{eff} scale(and the abundance variations) is well established. This may be extended to F stars taking into account our discussion about temperatures in Part 3.

Our paper in 1991 carries out second and fourth specifications. The spectrum analysis technique is exactly the same as that of this paper series and this warrants direct comparison. For 8 Am field stars the mean value of the iron abundance is globally the same (7.84 if that of the Sun is 7.51). The standard deviation of 0.2 dex may be entirely explained by the missing points 1 and 3. On the other hand, for seven normal A4 - F1 field stars, the iron abundance was found to be solar. The more likely explanation is that Fe overabundance of 0.3 dex in Am stars is almost unaffected by their very ages and degrees of evolution, but for normal A stars with normal calcium, iron is twice their initial solar value at the age of the Pleiades and became solar later.

The Li abundance behavior in the Pleiades A stars can be summarized as follows: The Am stars are clearly deficient in Li compared with the normal A stars, and the maximum Li abundance of the cluster is found in the normal A stars with a value marginally higher than that of meteoritic Li by 0.25 dex. Normal A stars, which are thought to undertake no Li burning during the pre-Main-Sequence lifetime and to be almost prevented from particle sorting by rapid rotation, seem to have preserved their original Li better than any other cooler stars of the Pleiades sequence.

In our 1991 paper, field Am stars have a slight tendency to be less abundant in Li than field normal A stars (by -0.25 dex); the dispersion of Li abundance is high in each (normal A or Am) group unlike Li in the Pleiades, which behave just as other-than-Li elements in the field. So the Li deficiency of Am compared with normal A stars is almost washed out in inhomogeneous field samples. The dispersion results would mean that the high dispersion in Li in field stars is not principally due to difficulties in determination of Li abundance compared with other elements because the Li I 6707Å doublet is weak, but that Li is more dependent on evolution, age (, and initial chemical composition) than other elements are.

The pre-Main-Sequence Orion stars with masses of 1.6 to 2.6 $M_{\odot}$ are studied for Li abundance by Cunha, Smith, and Lambert (1995) who improved a similar study with lower-resolution spectra by King (1993); these stars will evolve to become Main Sequence A and late B stars, similar to the stars studied here. Their mean LTE Li abundance for 10 Orion members is log N (Li) = 3.1 $\pm$ 0.4; a similar abundance is provided by our six Pleiades members since log N (Li) = 3.3 $\pm$ 0.35. The slight difference is not significant if we take into account that temperatures are determined with different methods. The observational scatter suggests that lumping stars into rotation groups and looking at their relative abundances is a better way to compare Orion stars with Pleiades stars, and in addition comparisons will be free, at the first approximation, of temperature scale problems. The three Orion stars with the lowest v sin i values do have a Li abundance below the other seven ones by 0.8 dex; this is very similar to the non rotating Pleiades A stars, i.e., the Am stars, which are Li deficient compared with the rotating Pleiades A stars, i.e., the normal A stars, by 0.65 dex. Following King (1993) who speculates that the Li-depleted, pre-Main-Sequence, Orion Ic stars with masses 1.5- 2.8 $M_{\odot}$ have rotationally spun down and are on their way to becoming Am stars, we can expect that the distinction for Li abundance between Am and normal A stars may have occurred during the pre-Main-Sequence evolution. Of course, this has to be confirmed: we assumed that, first, low projected rotational velocities of Orion stars mean low rotational velocities, and, secondly slow (resp. rapid) rotators at the epoch of Li differentiation on the pre-Main-Sequence are, too, slow (resp. rapid) rotators at the beginning of life on the Main Sequence in the mass range considered here.

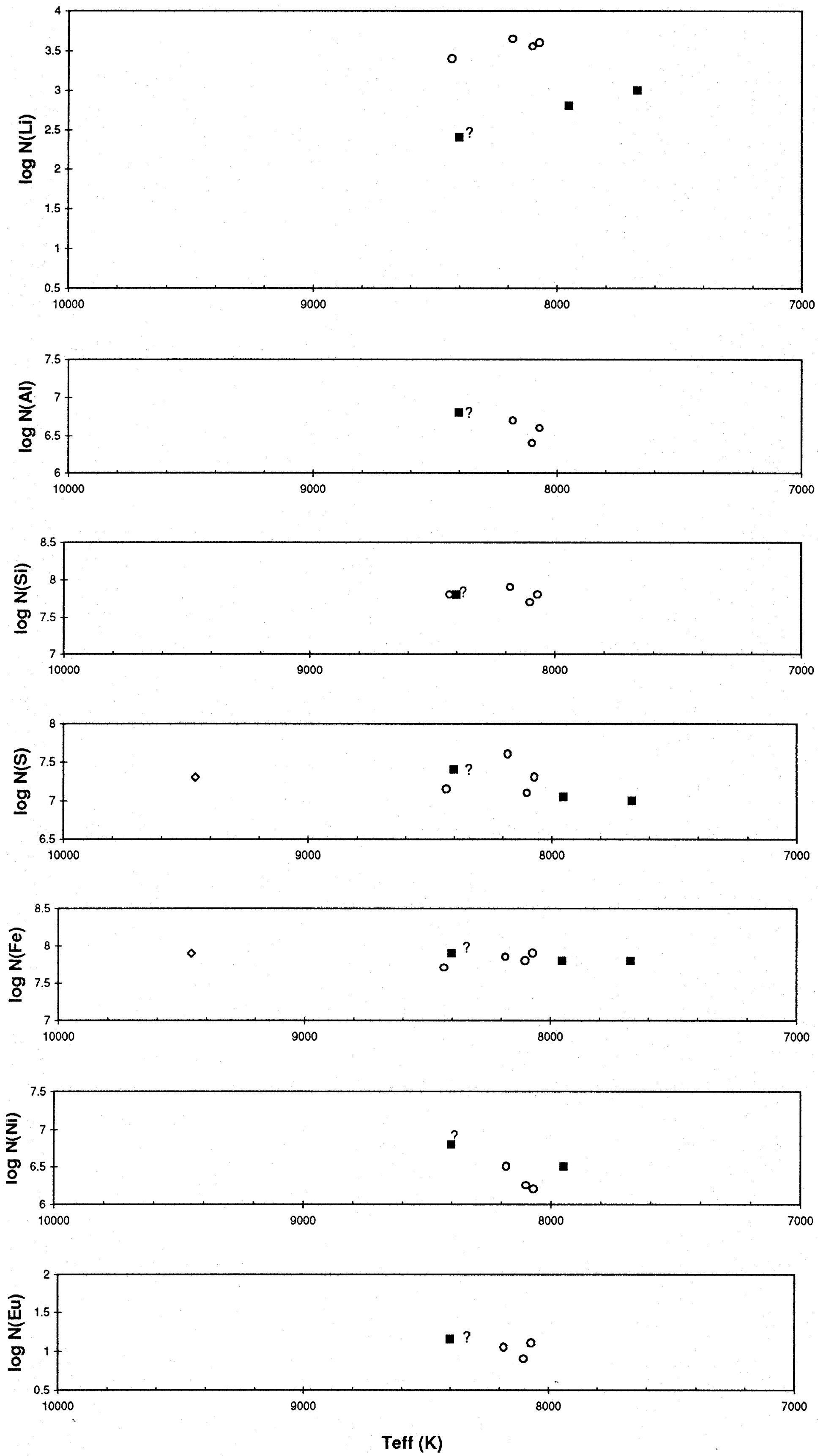

Fig. 2. Abundances of Li, Al, Si, S, Fe, Ni, and Eu (on the scale of log N(H) = 12.00) as a function of effective temperature T_{eff} for the Pleiades A stars. The open circles denote normal A stars, that is, normal Ca. The filled squares denote Am stars, that is, underabundant Ca. The uncertain member, HD 22615, is reported with a question mark

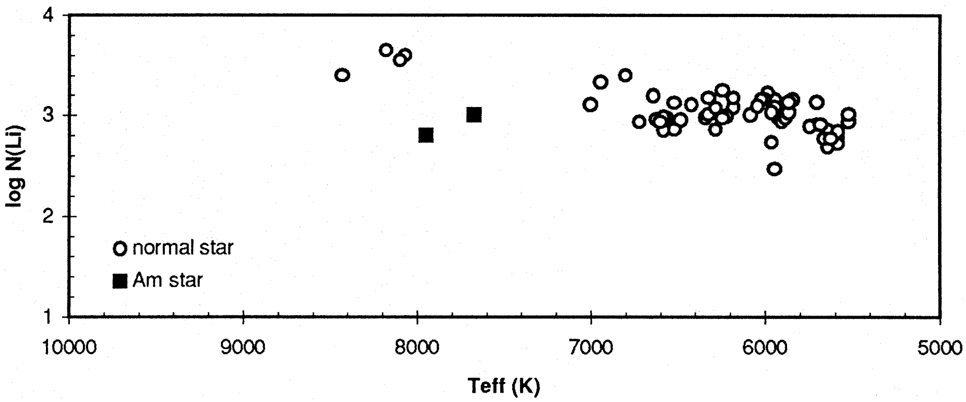

Fig. 3. The Li temperature profile of A stars with F and G stars (Soderblom et al. 1993b) in the Pleiades. The Am stars are plotted with filled squares

Our both analyses and the Orion analysis are LTE analyses. Non-LTE formation of Li I lines has been studied by Carlsson et al. (1994); non-LTE corrections are given for cool stars up to 7500 K. The corrections are negligible for the three Orion stars with low v sin i (and low Li) and they lower Li abundance by 0.2 dex for the seven members with high v sin i (and high Li) as seen in Table 8 of Cunha et al. (1995). The corrections around log N (Li) = 3.0 for the hottest stars considered by Carlsson et al. are nearly independent of Li abundance and weak (less than 0.1 dex); they lower Li results uniformly in our samples. In conclusion, if we take into account the non-LTE effects, our Li results and comparisons are left roughly unaltered; we merely observe that the Li deficiencies, "Am versus normal A Pleiades stars" and "low v sin i versus high v sin i Orion stars" become exactly the same.

Our Li results challenge predictions from model envelopes coupling diffusion and evolution in non-rotating Population I A stars. At the age of the Pleiades and $T_{\rm eff} > 7300$ K, only strong underabundances are found in the models assuming no mass loss (Richer & Michaud 1993) or a mass loss in the range 10^{-16} to 3 10^{-15} $M_{\odot}$ year^{-1} (Richer 1992). Moderate mass losses such as these are introduced to reproduce most heavy element anomalies of Am stars quantitatively; for Li it failed to reproduce the near normal Li observed. If the evolving models with gravitational settling and atomic diffusion plus mass loss are not questioned, at least another process is needed to compete with those already introduced. The Am stars are actually slow rotators and not "non-rotating" stars; they are likely affected by mixings induced by rotation and/or turbulence. On the other hand, computing more complex (and realistic) models increases the difficulties to test them since more free parameters are available for the adjustment of the models to the observations. It is true that observing other-than-Li elements of the same sample stars may put additional constraints upon the models. Thus the well-observed abundance of iron could be used, but the internal distribution of iron has not yet been computed in the evolving envelopes of Richer & Michaud. We merely note that improved radiative accelerations on iron (LeBlanc & Michaud 1995) are not found inconsistent with iron observed in Am Pleiades stars. The high Li abundance of fast rotators, normal A stars, is interpreted as evidence for an inhibiting process of Li depletion associated to rapid rotation; it may be the near initial value of Li (Richer & Michaud 1993). However, it is not clear that normal A stars are completely unaffected by settling and other processes if to a lesser extend than Am stars (Charbonneau & Michaud 1991), which has to be compared to observed Fe overabundance in Pleiades normal A stars (+0.3 dex from the initial value). In the framework of a diffusion-dominant description, another question should be tackled if Li differentiation should be really at work during the pre-Main-Sequence evolution as above suspected.

This first paper in the series deals with a small sample of stars at the beginning of their Main Sequence evolution. Observing similar stars in more distant clusters of similar age would be obviously interesting as telescopes and instruments allow us to reach them: We can test if the Pleiades cluster is peculiar in some way or accurately representative of the state of evolution of stars at its age, and confirm or not these present results. The other papers in the series will deal with Coma, Hyades, and Praesepe clusters, older than the Pleiades by one order of magnitude: A stars are well advanced in the Main Sequence evolution and the more massive ones are near the cluster sequence turnoff. Age dependence of the anomalies could be tested on the Main Sequence and comparisons done with stars that have just evolved off the Main-Sequence.

Acknowledgements. We acknowledge the excellent support by the CFHT staff, especially J.Glaspey, as well as the night help at the telescope. We are grateful to N.Grevesse, J.Sauval, and F.Castelli for trying to identify the europium blend. One of the authors (C.B.) wishes to thank in Lyon, France, the "Equipe Transfert" and the computing Department for their support. This research made use of the bibliographical stellar database, Simbad, operated at the "Centre de Données Stellaires" in Strasbourg, France.

References

Abt H.A., Levato H., 1978, PASP 90, 201
Anders E., Grevesse N., 1989, Geochimica et Cosmochimica Acta 53, 197
Beckers J.M., Bridges Ch. A., Gilliam L.B., 1976, A High Resolution Spectral Atlas of the Solar Irradiance from 380 to 700 nm, Sacramento Peak Observatory
Biémont E., Karner C., Meyer G., Träger F., zu Putlitz G., 1982, A&A 107,166
Blackwell D.E., Lynas-Gray A.E., Smith G., 1995, A&A 296, 217

Boesgaard A.M., 1987, ApJ 321, 967
Boesgaard A.M., 1989, ApJ 336, 798
Boesgaard A.M., 1991, ApJ 370, L95
Boesgaard A.M., Friel E.D.,1990, ApJ 351, 467
Burkhart C., Coupry M.F., 1989, A&A 220, 197
Burkhart C., Coupry M.F., 1991, A&A 249, 205
Carlsson M., Rutten R.J., Bruls J.H.M.J., Shchukina N.G., 1994, A&A 288, 860
Castelli F., 1994, private communication
Charbonneau P., Michaud G., 1991, ApJ 370, 693
Conti P.S., 1965, ApJS 11, 47
Conti P.S., Wallerstein G., Wing R.F., 1965, ApJ 142, 999
Conti P.S., Strom S.E., 1968, ApJ 152, 483
Coupry M.F., Burkhart C., 1992, A&AS 95, 41
Cowley A., Cowley C., Jaschek M., Jaschek C., 1969, AJ 74, 375
Cunha K., Smith V.V., Lambert D.L., 1995, ApJ 452, 634
Dworetsky M.M., Smalley B., 1996, in preparation
Gerbaldi M., Faraggiana R., 1991, MemSAIt 62,97
Gray R.O., Garrison R.F., 1987, ApJS 65, 581
Gray R.O., Garrison R.F., 1989a, ApJS 69, 301
Gray R.O., Garrison R.F., 1989b, ApJS 70, 623
Grevesse N., Sauval J.,1993, private communication
Griffin R., Griffin R., 1979, A Photometric Atlas of the Spectrum of Procyon (Cambridge)
Hartoog M.R., Cowley C.R., Adelman S.J., 1974, ApJ 187, 551
Hobbs L.M., Duncan D.K., 1987, ApJ 317, 796
Holweger H., Kock M., Bard A., 1995, A&A 296, 233
Johnson H.L., Mitchell R.I., 1958, ApJ 128, 31
King J.R., 1993, AJ 105, 1087
Kurucz R.L., 1979a, ApJS 41, 1
Kurucz R. L., 1979b, Dudley Obs. Rep. No. 14, 363
LeBlanc F., Michaud G., 1995, A&A 303, 166
Moon T.T., 1985, Commun. Univ. Lond. Obs. No. 78
Moon T.T., Dworetsky M.M., 1985, MNRAS 217, 305
Napiwotzki R., Schönberner D., Wenske V., 1993, A&A 268, 653
Pilachowski C. A., Booth J., Hobbs L.M., 1987, PASP 99, 1288
Renson P., 1988, A&AS 76, 127
Renson P., 1990, Bull. Inform. CDS No. 38, 151
Richer J., 1992, Ph.D. thesis, Univ. Montréal
Richer J., Michaud G., 1993, ApJ 416, 312
Rutten R.J., Van der Zalm E.B.J., 1984, A&AS 55, 171
Saxner M., Hammarbäck G., 1985, A&A 151, 372
Smalley B., Dworetsky M.M., 1993, A&A 271, 515
Smalley B., Dworetsky M.M., 1995, A&A 293, 446
Smith M.A., 1971, A&A 11, 325
Soderblom D.R., Stauffer J.R., Hudon J.D., Jones B.F., 1993a, ApJS 85, 315
Soderblom D.R., Jones B.F., Balachandran S., Stauffer J.R., Duncan D.K., Fedele S.B., Hudon J.D., 1993b, AJ 106, 1059
Souchay J., 1994, private communication
Spite M., 1989, private communication
Trumpler R., 1921, Lick Obs. Bull. X, No 333, 110

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