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The field Am and ρ Puppis-like stars: Lithium and heavier elements*

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Abstract. With observations at the Canada-France-Hawaii telescope, photospheric abundances of two evolved field Am stars, τ UMa and HR 178, have been determined for Li, Al, Si, S, Fe, Ni, and Eu by model abundance analysis. Thanks to these new determined abundances and the HIPPARCOS mission, making it possible to better estimate the evolutionary stage of field stars, one can consider the influence of evolution on the abundances of Am stars. No abundance trend for Al, Si, S, and Fe is found during Main Sequence evolution, up to its very last phases. The abundance of Li is, generally, cosmic. Large Li deficiencies may be observed in the very last phases (the "hook" region of the H-R diagram) and, too, on the red side of the Am phenomenon region where the ρ Puppis-like stars lie.

Key words. stars: abundances – stars: chemically peculiar – stars: individual: τ UMa – stars: evolution

1. Introduction

In a previous paper (Burkhart & Coupry 1991, hereafter Paper I), field A and Am-Fm stars have been studied by a model atmosphere abundance analysis. For Am stars, the abundances of Al, Si, and Fe are constant as a function of temperature; in contrast, the spread in Li abundance is larger than 1.0 dex with a group of stars around log N (Li) = 3.1 and a few Li-deficient stars. The conclusion was that these Li-deficient stars might be slightly evolved.

This paper aims at two objectives. First, with new observations of two evolved Am stars, τ UMa and HR 178, it is an addition to the abundance study of Paper I. Secondly, thanks to the HIPPARCOS mission, the evolutionary stage (and the mass) of all observed field stars is better known than in Paper I and we can re-estimate the influence of evolution on the abundances of Am stars. We compare our results to the theoretical ones from detailed evolutionary models (Richer et al. 2000; Richard et al. 2001).

2. The ρ Puppis-like star τ UMa (HD 78362) and the Am star HR178 (HD 3883)

The abundances of Li, Al, Si, S, Fe, Ni, and Eu have been investigated in the Am stars τ UMa and HR 178.

τ UMa belongs to the very small group of ρ Pup stars that Gray & Garrison (1989) defined by spectroscopic classification. These stars are unusually late and apparently evolved Am stars. It is important to study the abundance behavior of the Am phenomenon on its red upper boundary in the HR diagram and to have a better understanding of this ρ Pup group.

The results for the Am star HR 178 are given for 3 more elements than in Paper I. HR 178 is a sharp-lined star. Together with Procyon and the Sun, this star enables us to check the consistency of results obtained by the spectra from different telescopes and spectrographs used in our papers on cluster and field A stars (see Burkhart & Coupry 2000, and references therein).

2.1. Observations and data reduction

The bright stars τ UMa and HR 178 were observed using the Canada-France-Hawaii (CFH) 3.6 m telescope as a backup programme during very poor night sky conditions.

Stellar and observational data are collected in Table 1. The spectra were obtained by the f/7.4 Coudé spectrograph camera equipped with a Reticon detector (spectra covering 135 Å at a dispersion of 4.83 Å mm^{-1}).

The reduction technique and abundance determination procedures were the same as in Paper I (see also Coupry & Burkhart 1992). The data reduction was carried out with codes

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

Table 1. Observational data.

	Sp type	V	Exp time (mn)	JJ (d) –2 440 000	Remarks
HR 178 HD 3883	A7 m Cowley&al 1969	6.1	20	7890.74	
τ UMa HD 78362	A3-F2-F5 (Ib) Gray & Garrison (1989)	4.7	40	7892.08	SB P = 1062.4 d e = 0.48

written by M. Spite (private communication); abundances were derived using synthetic spectra computed from Kurucz (1979a,b) model atmospheres with $T_{\rm eff}$, log g derived from $uvby$, β photometry calibration (Moon 1985; Moon & Dworetsky 1985); these values are given in Table 3. A typical error in β, equal to ±0.010 mag, produces an error in temperature of ±100 K. It corresponds to an error of about $\Delta(\log N)$ = ±0.06 or 0.07 dex in the case of neutral species. The 1979 Kurucz models were used in order to maintain consistency with Paper I, our purpose being to compare the abundance patterns between the stars under study. Tests show that newer Kurucz models introduce small abundance differences without altering the relative abundances considered in this paper.

The equivalent widths of the set of lines for the two stars, τ UMa and HR 178, 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 I line. When the equivalent width of each line of the blend is not evaluated, we compare the whole observed blend to a computed synthetic blend, the chosen Fe abundance in the computation being the one independently obtained from the FeI single lines.

The abundance results are given in Table 3 with some results of Paper I added; we have put together in this table all the field Am stars whose Li I doublet was measured by us. We omitted the double-lined spectroscopic binaries (SB2) since no precise results could generally be reached. Regarding HR 178, the Li, Al, Si, and Fe abundances (as well as the microturbulent velocity $v_{\rm t}$) mentioned in this paper are very close to those in Paper I, thus confirming the consistency of results obtained from different configurations of the same instrument.

For τ UMa and HR 178, a dozen Fe I lines are used to estimate the Fe abundance (see Table 2). The dispersion of the values gives an idea of the internal precision for a given star in favourable cases (high S/N spectra, no SB2, low $v \sin i$): σ = 0.03 dex (n = 12) for τ UMa and 0.06 dex (n = 11) for HR 178.

We recall the bias encountered in studying lithium in that range of temperature. Owing to the weakness of the Li I doublet, all the stars in Table 3 have projected rotational velocities $v \sin i$ less than ~50 km s^{-1}. Thus, a selection effect exists in our sample, since the mean projected rotational velocity of Am stars is ~50 km s^{-1}.

Table 2. Measured equivalent widths (mÅ) of τ UMa and HR 178. The contribution of a weak line is marked "bd"; in that case its equivalent width is included in that given for the main line of the blend.

	λ	Mult		log *gf*	tau UMa	HR 178
NiI	6635.137	264	4.42	–0.80	46	
Ni I	6 643.638	43	1.68	–2.10	105	58
Eu II	6 645.127	8	1.38	0.35	46	29
Fe I	6 677.997	268	2.69	–1.67	148	122
Al I	6 696.032	5	3.14	–1.62	25	15
Fe I	6 696.322	1255	4.83	–1.60	14	9.5
Al I	6 698.669	5	3.14	–1.91	13.5	9.5
Fe I	6 699.136	1228	4.59	–2.17	6	5
FeI	6703.576	268	2.76	–3.15	16	9
Fe I	6 705.105	1197	4.61	–1.20	40	28
Fe I	6 707.449			–2.20	9	bd
Li I	6 707.760	1	0.00	0.00	bd	18.5
Li I	6 707.980	1	0.00	–0.30	bd	bd
FeI	6713.745	1255	4.79	–1.59		12
FeI	6715.386	1174	4.61	–1.52	20.5	13
FeI	6716.252	1225	4.58	–1.84	11.5	8
Fe I	6 717.527	1194	4.61		bd	bd
Ca I	6 717.687	32	2.71		54	50
Si I	6 721.844	38	5.86	–1.20	44	21
FeI	6725.364	1052	4.10	–2.30	10.5	
Fe I	6 726.673	1197	4.61	–1.18	41.5	30
FeI	6733.153	1195	4.64	–1.53	22	13.5
Si I	6 741.629		5.98	–1.62	18.5	6.5
FeI	6745.984	1005	4.07	–2.74	4.5	
FeI	6750.164	111	2.42	–2.78	54.5	37
FeI	6752.716	1195	4.64	61.33	31.5	26.5
Fe Ip	6 756.568	1120	4.29	–2.61	bd	5.5
S I	6 757.195	8	7.87	–0.21	88	66.5

2.2. Abundance pattern

The stars in Table 3 are shown in part of the observational H-R diagram, $M_V-(B-V)$ (Fig. 1, cf. Sect. 3.1) where A-F stars lie. τ UMa and ρ Pup lie in the same region of the H-R diagram. Their abundance patterns are close to one another for Li, Al, Si, and Fe and we stress that Li is largely deficient. (In this work, the so-called galactic value log N(Li) = 3.1, where log N(H) = 12.00, is adopted as the normal Li abundance.) The other elements are overabundant by 0.3 to 0.5 dex relative to the Sun. So, we add a point to the properties of the ρ Pup stellar group.

The Am stars of Table 3 are subdivided into a Li-cosmic group (the 4 hottest stars) and a Li-largely-deficient group (3 stars deficient by −1.0 dex or more). Their Al, Si, and Fe patterns are close to each other, whether the Li-cosmic or the Li-deficient group was measured. The mean of each abundance is +0.2 to +0.4 dex relative to the Sun, the standard deviation being equal to or less than 0.2 dex.

The Am field stars form a group with homogeneous metal overabundances except for lithium. However, we note that for

Table 3. Metal abundances (on an absolute scale and with $\log N(\mathrm{H}) = 12.00$) of field Am stars derived by our homogeneous analysis (this work (bold-faced type) and Paper I). The last line gives the solar abundances chosen in this study so as to possibly consider abundances normalized to the Sun, $[El]$. As usual, the symbol $[X]$ for any quantity X means $\log (X)_\star - \log (X)_\odot$.

	Teff (°K)	log *g*	v_t	log *N* (Li)	log *N* (Al)	log *N* (Si)	log *N*(S)	log *N* (Fe)	log *N* (Ni)	log *N* (Eu)
ζ^1 **Lyr**	8170	3.9		3.3	6.9	7.8		8.1		
HD 173648										
15 Vul	8040	3.7		3.2	6.7	7.4		7.5		
HD 189849										
32 Aqr	7870	3.9	3.5	3.0	6.75	7.7		7.9		
HD 209625										
HR 178	**7800**	**3.65**	**4.5**	**3.11**	**6.82**	**7.67**	**7.27**	**8.10**	**6.81**	**1.48**
HD 3883	7800	3.8	4.2	3.1	6.8	7.65		8.1		
γ **Cap**	7520	3.95		≤2.0	6.8	7.8		8.0		
HD 206088										
τ **UMA**	**7390**	**4.0**	**4.1**	**≤2.2**	**6.87**	**7.96**	**7.43**	**8.08**	**7.10**	**1.64**
HD 78362										
ρ **Pup**	6920	3.7	4.1	≤1.4	6.8	7.9		7.9		
HD 67523										
Sun					6.47	7.55	7.21	7.51	6.25	0.51

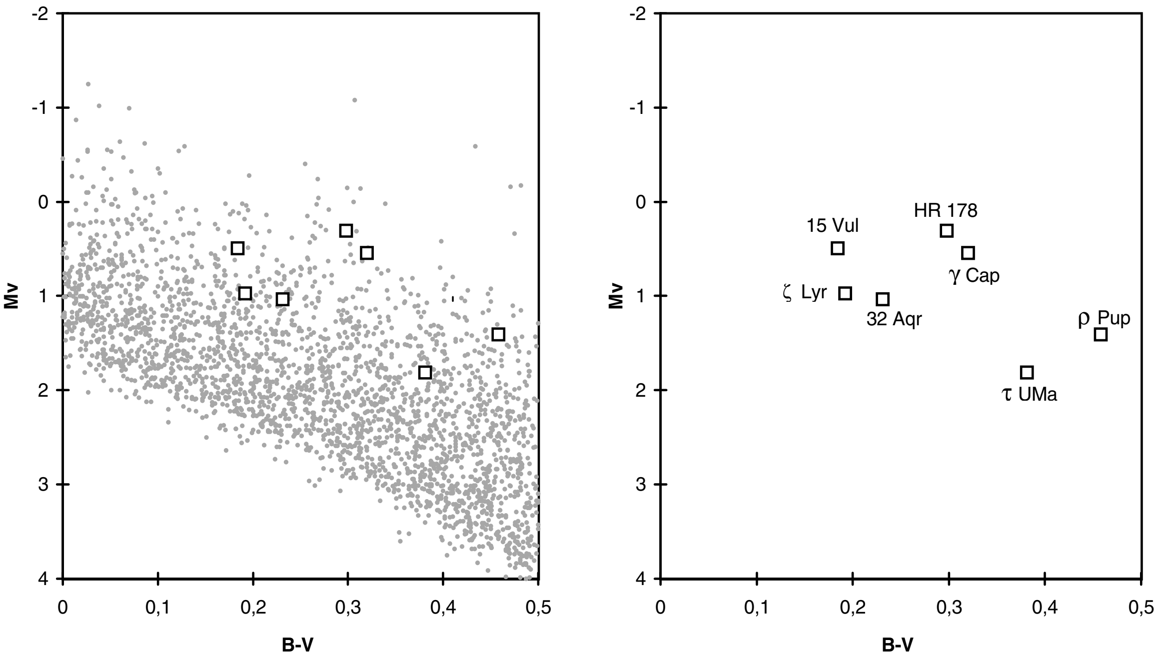

Fig. 1. Color–magnitude diagram for A-F stars with the studied stars. The data are taken from the HIPPARCOS catalogue imposing $V < 7$, $\sigma(B-V) < 0.025$, and $\sigma(\pi)/\pi < 0.1$. Note that $\sigma(\pi)/\pi = 0.11$ for HR 178. No dereddening is applied.

each element the overabundance for 15 Vul is the lowest, almost solar, and for τ UMa it is one of the highest.

2.3. Lanthanides and lithium identification

This homogeneous behavior of abundances can be compared to the qualitative results obtained by Cowley (1983) from a cluster analysis by the method of Wavelength Coïncidence Statistics (WCS) with lines of the second spectra of lanthanide rare earths. In the class with a strong lanthanide spectrum, 3 Am stars of this work are very closely linked: 32 Aqr, HR 178, and τ UMa. The direct comparison is straightforward for 32 Aqr and HR 178; their spectra are very similar, in agreement with the abundances given in Table 3 and the similar lanthanide spectrum suggested by Cowley. For τ UMa, if we take

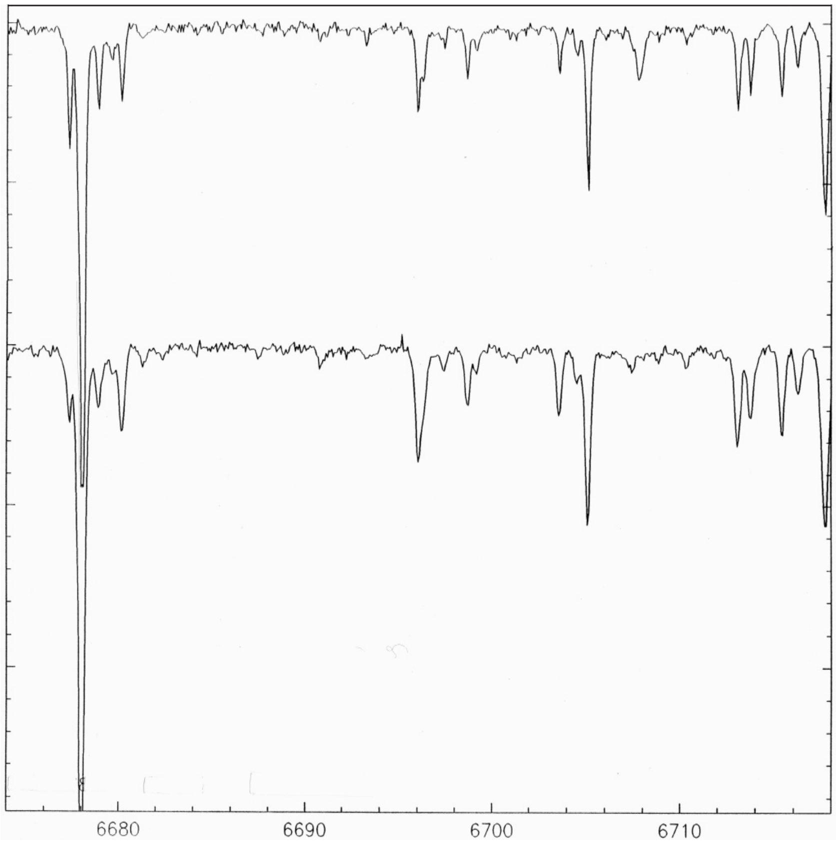

Fig. 2. Spectra of HR 178 (*top*) and τ UMa (*bottom*). The vertical shift corresponds to 0.2 fraction of intensity; the horizontal scale is in Å.

into account the cooler temperature, the spectrum is similar except for stronger Si I lines and Li I blend missing. Figures 2 and 3 compare a fragment of spectra for HR 178 (top) and τ UMa (bottom).

The identification of the λ 6708 feature with the Li resonance doublet has been questioned in Barium stars (Lambert 1993), in Ap stars (Faraggiana et al. 1996), in post-AGB stars (Reyniers et al. 2002), and in Przybylski's star by Shavrina et al. (2003). The most likely alternative identification or contamination of this feature would be that of Rare Earth elements. For HR 178 and τ UMa, if we put together the similarity between their spectra with the exception of the λ 6708 feature (Figs. 2 and 3) and the similarity between their lanthanide spectra (Cowley 1983), it appears that the identification of Li in Am stars can no longer be questioned.

Cowley (1983) points out the dominance of the Ce II spectrum among the lanthanide spectra. After Reyniers et al. (2002) suggested that the λ 6708 feature in post-AGB stars is likely due to a Ce II transition at 6708.099 Å, synthetic spectra of HR 178 were calculated, either by using the Kurucz (1993, CD Rom 13) line list where the Ce II 6708.099 is not present, or by adding the new identifications and log gf of Ce II available in the "Database on Rare-Earths At Mons University" (DREAM). The input Ce abundance is that found by van't Veer et al. (1988) in HR 178: log N(Ce) = 3.2. The contribution of the Ce II line to the λ 6708 feature has been found to be negligible. So, the identification of Li is strengthened in Am stars, while this is not the case with some Ap stars as, for example, HD 188041 where Ce II 6708.099 contributes significantly to the λ6708 feature.

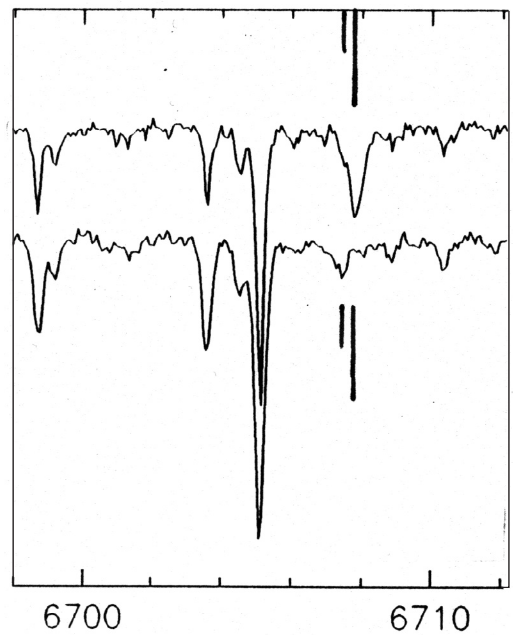

Fig. 3. Magnified Li region of Fig. 2 with marks for 6707.5-FeI and 6707.8-LiI.

3. The H-R diagram

3.1. The observational H-R diagram

The HIPPARCOS mission has made it possible to constrain the positions of near field stars in the color–magnitude diagram with higher accuracy than previously. With the trigonometric parallaxes of each star, the V-magnitude and $(B-V)$ index coming from ground-based measurements are given in the HIPPARCOS catalogue. We select all the normal A or F stars with $(B-V)$ in the interval [0.0; 0.5] imposing $V < 7$ and $\sigma(B-V) < 0.025$ with $\sigma(\pi)/\pi < 0.1$. The resulting $M_V - (B-V)$ color-absolute magnitude diagram is shown in Fig. 1, as well as the positions of the stars in Table 3. All these stars, for which confident abundances have been obtained, lie in the upper part of the Main Sequence strip and are, therefore, well advanced in their Main Sequence evolution.

The stars HR 178 and γ Cap are very close to each other in the H-R diagram; so are their abundances of Al, Si, and Fe. Why is lithium so different, at least by a factor of 10? We might think of differences in pre-Main-Sequence history, or in rotational velocity ($v \sin i = 18$ and 31 km s^{-1} resp. according to Abt & Morrell 1995), or possibly different phases in the terminal Main Sequence evolution (as will be considered in the next paragraph).

3.2. The H-R diagram, log $L/L_\odot$ – log T_{eff}

To obtain some information on basic parameters, masses and ages, we turn to a theoretical H-R diagram where log L is plotted against log $T_{\rm eff}$. The stars in Table 3 are placed on the grid of Fig. 4, where the evolutionary paths are taken from Schaller et al. (1992) and the isochrones from Meynet et al. (1993). Two groups of stars are obvious:

- 2 stars with $M < 2\ M_\odot$ and age $\sim 10^9$ yr.
  τ UMa ($\sim 1.8\ M_\odot$) and ρ Pup have positions near the red edge of the Instability Strip (and the red boundary of the Am phenomenon). The star ρ Pup is a δ Scuti star and more evolved than τ UMa; ρ Pup may be ending its phase of central hydrogen burning and consequently would have experienced changes in the outer layers of its stellar envelope. All this has not prevented the stars from having similar abundance patterns, particularly a large deficiency of lithium (cf. Sect. 2.2).
- 5 stars with $M > 2\ M_\odot$ and age $< 10^9$ yr.
  The position of 15 Vul in the theoretical H-R diagram does not provide any clue as to why this star has practically solar abundances for the few elements examined: Al, Si, and Fe. The 3 stars 15 Vul, ζ^1 Lyr, and 32 Aqr have cosmic Li abundance, which means that no Li depletion has yet occured.

On the other hand, the positions of HR 178 and γ Cap in the region of "blue and red hooks" (Fig. 4) may be a clue to their difference in Li abundance. In that region, several evolutionary paths and isochrones cross at one point. We can imagine that neither star is in the same last phases of the Main Sequence evolution, even though both stars are very close to each other in the diagram; for example, the Li-cosmic star, HR 178, may

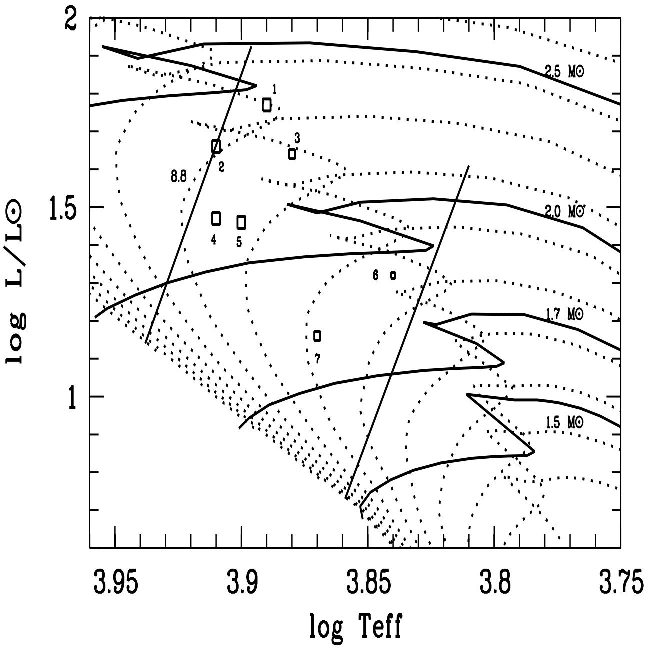

Fig. 4. The H-R diagram, log $L/L_\odot$ – log $T_{\rm eff}$, with the studied stars (1: HR 178, 2: 15 Vul, 3: γ Cap, 4: ζ^1 Lyr, 5: 32 Aqr, 6: ρ Pup, 7: τ UMa). The representative points are drawn with a size taking into account the Li abundance. Evolutionary paths (continuous line) are those by Schaller et al. (1992) and isochrones (dotted lines) those by Meynet et al. (1993). The ages (yr) on the isochrones are given in logarithmic scale at each 0.1 interval. The only value of the age indicated, 8.8, is that of the Hyades and Praesepe clusters. The straight lines show the approximate blue and red boundaries of the Instability Strip (Turcotte et al. 2000).

be evolving towards the end of the core hydrogen burning phase (red hook), whereas the Li-deficient star, γ Cap, may be experiencing the onset of shell hydrogen burning (blue hook); the temperature-fragile element Li might be rapidly affected in the envelope of γ Cap.

We can directly compare the abundances mentioned in this work with those in open clusters (Burkhart & Coupry 2000), taking advantage of the identical process used to obtain the abundances of both field and cluster stars (observations, data reduction technique, temperature determination, model atmospheres). The isochrone 8.8 of Fig. 4 corresponds to that of the Hyades and Praesepe clusters ($\sim 0.65 \times 10^9$ yr): the ages are the same (or somewhat higher) for 5 stars (ζ^1 Lyr, 15 Vul, 32 Aqr, HR 178, and γ Cap); ρ Pup and τ UMa are older than these clusters. According to their position in the H-R diagram, the 5 stars are more massive than those analyzed in the clusters and consequently more evolved. For these stars the abundance patterns for Al, Si, S (only 2 stars) and Fe are the same, to within ± 0.1 dex, as those of cluster stars.

The lack of an abundance trend as a function of age and/or evolution is extended to a somewhat larger region of the H-R diagram: ages up to $\sim 10^9$ yr, masses up to 2.5 $M_\odot$, and evolution up to the very last phases of the Main Sequence life.

For 4 field stars (ζ^1 Lyr, 15 Vul, 32 Aqr, and HR 178): log N(Li) = 3.15 dex with $\sigma = 0.1$ dex; for 16 cluster stars (out of 18): log N(Li) = 2.95 dex with $\sigma = 0.1$ dex. In the atmospheres of non Li-deficient stars, a mild Li enrichment with age cannot be excluded after 0.65×10^9 yr. No cluster star was studied in the regions of the H-R diagram where Li-deficient field stars were found: the "hook" region (γ Cap, ρ Pup) and an upper red part of the Instability Strip (ρ Pup, τ UMa). The cluster star 16 Ori is not distinguished from the others in the same region of the H-R diagram, except for its Li deficiency.

4. Discussion and conclusion

Among the Am stars, Gray & Garrison (1989) have isolated a "ρ Pup" class of late and evolved stars which defines the red boundary of the Am phenomenon in the H-R diagram. In this work, 2 stars of this class show similar abundance patterns (in particular a large Li deficiency). The reality of the "ρ Pup" group is thus strengthened and extended from spectral classification to elemental abundances.

For the evolved Am stars HR 178 and τ UMa the newly determined abundances from observation can be compared to the computed abundances calculated for 24 chemical species from detailed evolution models (Richer et al. 2000; Richard et al. 2001). This comparison requires knowledge of the mass of the star; the more element abundances we get, the more observational constraints we fix to the models of Richer et al. (2000) and of Richard et al. (2001).

For HR 178, the mass determination, as also the actual phase of its evolution, is not univocal; this prevents us from exploring the relation between the available abundances of many elements (van't Veer et al. 1985, 1988, 1989; Hui-Bon-Hoa 2000, and this work) and the evolutionary stage of this star through the Richard et al. (2001) models. The ambiguity in the mass determination, due to the position of the star in hook regions of the evolutionary paths, is of the same order as that of the observational errors, this last being of the order of 0.1 $M_{\odot}$. It would be interesting to have access to a 2.5 $M_{\odot}$ model with different turbulence models by Richard and coworkers and to compare it to the many abundance data observed for HR 178.

HR 178 is not the only star for which the mass determination is not univocal, as can be seen from Fig. 4. For HR 178 or γ Cap, the lifetimes on different portions of these evolutionary tracks are such that the amount of time required to move from the continuous redward path to the blue hook or even to the redward of the upper hook is small, of the order of 7% of the time spent on the Main Sequence.

For τ UMa the mass has been determined in Fig. 4 to be 1.8 $M_{\odot}$. According to the errors on the determination of $T_{\rm eff}$ and $\log L/L_{\odot}$, we have estimated an upper limit of 0.1 $M_{\odot}$ for the error on the mass.

The recent observed abundances (van't Veer et al. 1989; Hui-Bon-Hoa 2000, and this work) of τ UMa have been compared to those computed by Richard et al. (2001). In their Fig. 15, these authors show surface abundances calculated in 1.5 $M_{\odot}$ and 2.0 $M_{\odot}$ models with different turbulence models, which introduce the decisive parameter, namely, the mass of the mixed zone between the Fe convection zone and the He convection zone. These authors compare the observed abundances of the 5 elements (Mg, Ca, Cr, Fe, Ni) derived by Hui-Bon-Hoa (2000) with their computations. We add the abundances of OI taken from van't Veer et al. (1989) and those of Li, Al, Si, S, Fe, and Ni from this paper.

The abundances of the 2 elements shared by these authors, Fe and Ni, are very close to each other, with closely related abundance analyses (and temperature scales). The new observed abundances fit both the 2.0 and 1.5 $M_{\odot}$ models with the highest turbulence, but the 2.0 $M_{\odot}$ model fits better. We note, particularly, the agreement between the calculations and the large deficiencies observed for lithium (this work) and oxygen, the evaluation of which takes into account NLTE effects (van't Veer et al. 1989). In the quoted Fig. 15 of Richard et al. (2001), of the elements studied in the present paper, Si and S are some of the more sensitive ones to turbulence and mass, as well as being among those for which the highest discrepancy with the computations is observed. Thus they can be efficiently used to test turbulence models. The discrepancy of Li and O abundances suggests an opposite trend of these elements with respect to Al, Si and S.

The region of the H-R diagram explored thanks to field and cluster stars corresponds to masses ranging from 2.5 to 1.8 $M_{\odot}$ and ages from 0.08 to 1.0×10^9 yr. The lack of an abundance trend for Al, Si, S, and Fe for Am stars during Main Sequence evolution (Burkhart & Coupry 2000) is extended to the very last phases of that evolution and to an upper red part of the Instability Strip. The observations agree reasonably well with the calculations (Richer et al. 2000; Richard et al. 2001).

The role of evolution (around the last phases of the Main Sequence evolution) on the Li deficiencies suggested in Paper I is better stated. Large Li deficiencies may be observed in the very last phases (the "hook" region). They are also observed in the red part of the Instability Strip. In both cases, important changes in the stellar envelope structure can be invoked to produce deficiencies of the fragile Li element. On the other hand, the Li-cosmic field stars show a marginal Li enhancement compared to their less evolved cluster counterparts of about the same age, but with smaller masses.

To confirm our results and hypothesis it would be obviously desirable:

- to observe a large sample of field Am star to better scrutinize the distribution of Am stars in the H-R diagram;
- to increase, for a few stars, the chemical species studied through a wider spectral range analysis.

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