THE Fm-Am STARS: OBSERVED ANOMALIES

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ABSTRACT. The classical anomalies of Am-Fm stars are reviewed. Progresses already made, or expected to come, due to improvements in observations thanks to the new generation of telescopes and high S/N detectors as well as from theoretical advances are described. Current unsolved problems are identified.

1. Introduction

Thanks to a very efficient mixing mechanism (convection) stars on the lower main sequence cooler than the sun retain in their atmosphere the chemical composition of the matter from which they formed. This happy situation stops holding at about the spectral type F0, or effective temperature 7000 K. Then, the convective zone becomes very shallow and does not represent more than an extremely tiny fraction of the mass of the star. Selective separation of elements can then take place (Michaud's paper in this symposium) and observation shows that chemical composition anomalies can occur from this entry point up to much hotter stars,actually B stars with effective temperature of about 20 000 K. For still hotter stars, violent winds seem to prevent such fractionations to take place. The Am stars are those at the cool end of this zone,without strong organized magnetic fields. We enter here the "big mess" of chemically peculiar stars, including the Ap stars and the Bp stars, with and without magnetic fields.

2. Anomalies as established by classical photographic spectrography

Let us recall that metallic-line stars have been recognized by Titus and Morgan in 1940 and that their identification in the MK classification was defined by Roman, Morgan and Eggen in 1948.
In short they stand out of the normal MK classification for two reasons:

G. Michaud and A. Tutukov (eds.), Evolution of Stars: The Photospheric Abundance Connection, 99–110.

the Ca II K line is weak for the strengh of the Balmer lines, whereas iron metallic-lines are in general too strong for the Balmer lines strength. A modern way of classifying them is to give the three spectral types as shown here :

kA2hF0mF3 (classification of the star 63 Tau)

Conti (1970) has extended the search of Am stars among the early A-type stars and has defined the "hot" Am stars. Conti's definition of Am stars does not require the presence of both anomalies (weak K line and strong iron lines) but only one of those.
The chemical analyses of all these stars have revealed a number of anomalies which have been reviewed by Conti (1970) , by S.Wolff (1983)and more recently by Boyarchuk and Savanov (1986). We refer the audience to these papers for more details on "classical" anomalies in Am-Fm stars (we shall further on use "Am stars" instead of "Am-Fm stars" for sake of concision). Let us summarize briefly the well established anomalies.

a) The abundance of Calcium and Scandium are down by a factor 5 to 10 although this anomaly can be marginal in some mild Am stars.

b) among the light elements Carbon seems also to be deficient

c)the iron-group elements are overabundant by a factor 2 or 3

d) some rare-earths are overabundant by a factor 10 or more, but not all of them.

On top of these abundance anomalies other global properties make Am stars different of normal A or F type stars classified "normal"

e)<u>rotation</u>: the mean projected rotational velocities of Am stars is much lower ($\simeq$ 40 km/s) than for normal A stars (120 km/s).

f)<u>binarity</u>: Abt (1961) discovered that Am stars are all or almost all spectroscopic short period ($<P> \simeq$ 10 days) binaries. This result is very probably the explanation of the low rotational velocity of the group.

g) <u>microturbulence</u> in Am stars was found to be fairly high (5 to 6 km/s) in the 70s, but recent work do not support such high values (rather 4 kms^{-1}), and these values do not seem specific to Am stars but to all stars of the same effective temperature.

h) <u>age</u>: Am stars are never very evolved so their ages range from a few 10^6 year to 1 Gy.

i) <u>place in H.R. diagram</u>: the effective temperatures of Am stars range from 7000 K to 9000 K or 10 000 K if hot Am stars are included.Their gravities extend from main sequence (log g = 4.3), to slightly evolved (log g = 3.5).

3. The effective temperature problem

The abundances found in metallic-line stars are of course dependent upon the effective temperature and gravity adopted in the analysis. There is unfortunately a very poor agreement in the effective temperatures found for the same object by different authors.

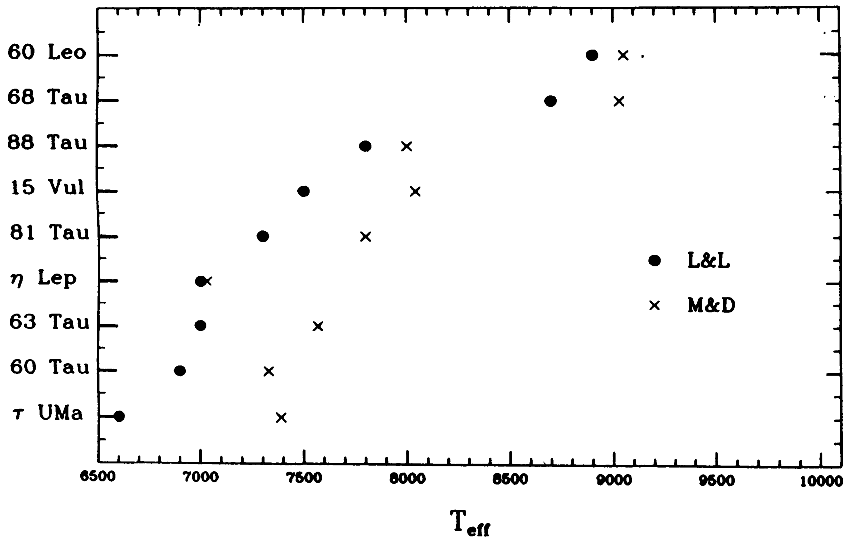

Fig. 1. Effective temperatures of Am stars according to Moon and Dworetsky and Lane and Laster. Note that η Lep,a normal F star,is the only one with perfect agreement between Moon and Dworetsky and Lane and Lester.The star 88 Tau has been removed, being found to be a quintuple system (Burkhart *et al.* 1988).

Fig.1 shows the discrepancy between Dworestky and Moon (1986) and Lane and Lester (1984) for the effective temperatures of 8 Am stars. Clearly the discrepancy is larger for cool Am stars (actually Fm stars) with strong metallicity.The discrepancy is at first view surprising because , after all, both methods are based on the energy distribution of the stars from UV to yellow (although Lane and Lester have a more extended UV but they gave a low weight to this part of the spectrum). The difference comes mostly from the calibration procedure. Moon and Dworetsky(1985) have calibrated with stars of known basic parameters, whereas Lane and Lester have taken the theoretical energy distributions of Kurucz's models as exact, with no corrections. It is absolutely necessary to clear out this problem because the 600 K, or so, temperature difference between these authors, is just enough to make Am stars iron-rich (Moon and Dworetsky temperatures) or not iron-rich (Lane and Lester temperatures).

We have decided to consider the typical case of 63 Tau for which much information is available and for which we had obtained high quality H_{α}

https://doi.org/10.1017/S0074180900227290 Published online by Cambridge University Press

and H_β profiles at the Observatoire de Haute Provence (with a CCD detector).
Fig.2 gives the position of the (T_{eff}, log g) points representing the models adopted by various authors for 63 Tau and to which we have added the points of Lane and Lester and Moon and Dworetsky.

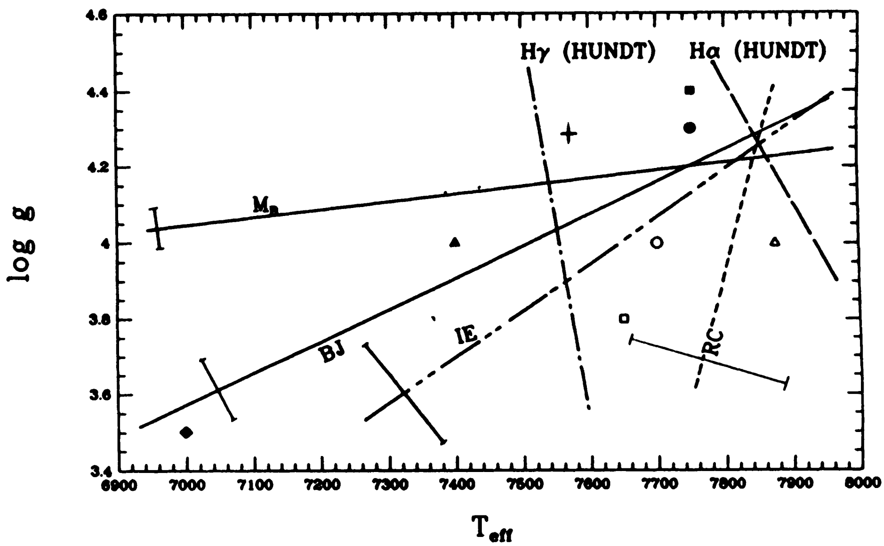

Fig.2. Location of the models used by several authors in the plane (Teff, log g) for the analysis of the Am star 63 Tau (adapted from Hundt 1972). The symbols are as follows:
■ Van't Veer 1963- □ Conti 1965- △ Baschek and Oke 1965- △ Oke and Conti 1966- ○ Smith 1971- ● Hundt 1972- + Moon and Dworetsky 1986- ◇ Lane and Lester 1987
The straight lines give the constraints corresponding to various observational criteria: Absolute bolometric magnitude, revised for a distance modulus of the Hyades of 3.25, Balmer Jump value, Ionization equilibria, Red Continuum, H_α, H_γ line profiles (Hundt) with estimated errors. Note that the constraints brought by the Balmer line profiles are with a more exact broadening theory now represented by a vertical strip at 7300 ± 100 K.

We have studied 63 Tau versus Procyon differentially in order to eliminate zero point problems. It turns out, as it is visible in the Poster "*Effective Temperature of the classical Am star 63 Tau from Balmer line profiles*" by C. Van't Veer *et al.* that *(i)* the effective temperature difference between 63 Tau and Procyon is 800 K , *(ii)* 63 Tau is iron-rich by 0.5 dex with respect to Procyon (Fig 3). If we accept the well documented values of 6500 K effective temperature and solar chemical composition for Procyon (Steffen 1985) this leads to an effective temperature of 7300 K for 63 Tau. Interestingly, Smalley and Dworetsky using H_β and H_γ find the same effective temperature for

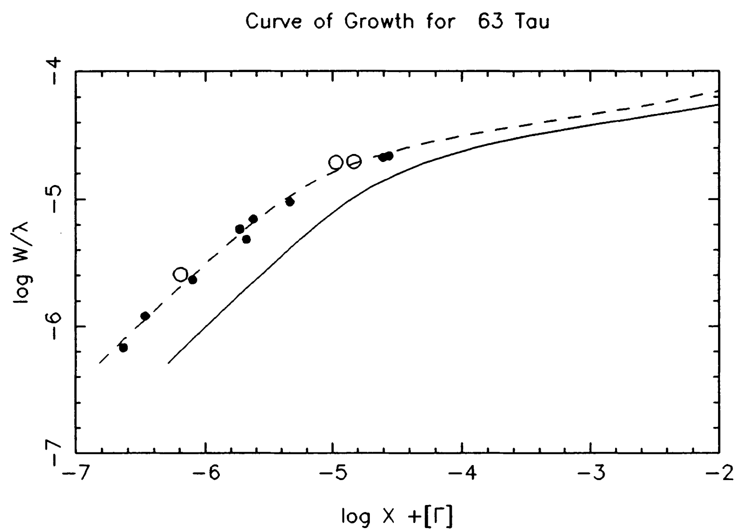

Fig. 3. Curve of growth for neutral (•) and (o) ionized iron lines. The horizontal shift measures the iron overabundance with respect to Procyon. The microturbulence assumed for Procyon is 2.1 kms^{-1} and the microturbulence found for 63 Tau 3.3 kms^{-1}. This last result is dependent upon the value adopted for [Fe/H].

63 Tau (see their poster "*The effective temperature of late A and early F stars from Balmer line profiles*"). Another, quite different method is presented in another poster by Megessier and Van't Veer "*Effective temperatures of Am stars by the infrared-flux method*" . This method (also called the Shallis and Blackwell method) is the closest to the actual definition of the effective temperature. The result T_{eff}= 7160 ± 70 K is only 140 K below the preceeding one, and does not include any correction for the presence of a red companion, which may very well raise the temperature by 100 K or so . The enormous range in effective temperature (from 7000 to 7870 K of fig.2 seems therefore, thanks to very recent work, possibly reduced to about 7200- 7400 K. As we shall see in a further section this does not mean that proper abundances are obtained with a model atmosphere having this effective temperature. As most authors have done, in order to obtain agreement between neutral lines and ionized lines, a model with a "nominal" effective temperature 250 or 300 K higher than the true effective temperature must be used. For a more rigorous approach , see the section dealing with departures from LTE.

4. New results obtained with high S/N ratio

4.1 LITHIUM ABUNDANCES IN Am STARS

Burkhart *et al.* (1987, 1988, 1989) have recently investigated the lithium content of Am stars in the Hyades and in the field. Fig.4 summarizes their findings.

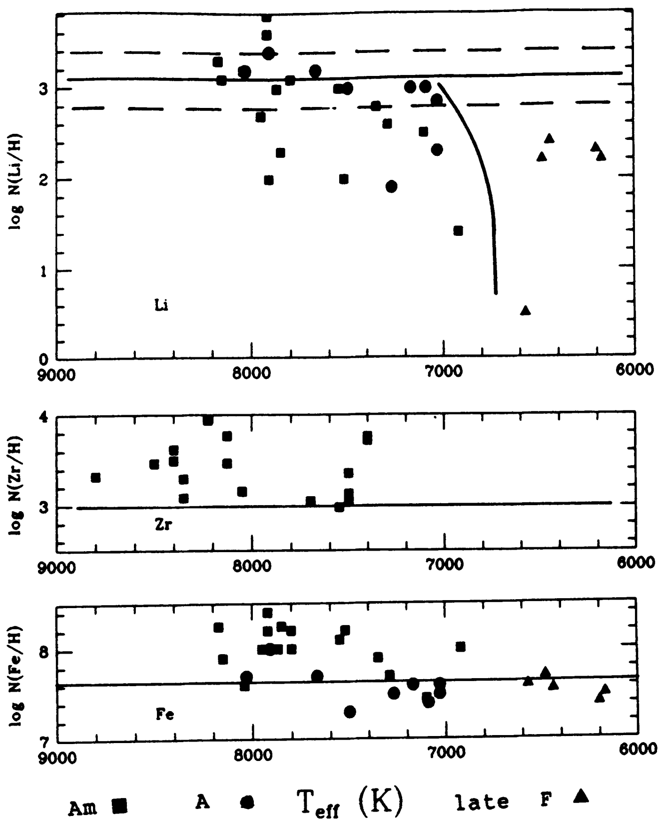

Fig. 4. Abundances of Li, Zr, and Fe (on the scale $\log(N_H) = 12$) as a function of effective temperature. The solid horizontal lines display mean abundances of normal middle-late A stars for Zr and Fe, and the so-called galactic abundance $\log N_{Li} = 3.1$ for Li. Note the similar behaviour of Zr and Fe.

Lithium is either with the standard cosmic abundance found in very young stars, or underabundant. It is never strongly overabundant, contrary to what the diffusion theory predicts in absence of mass-loss

https://doi.org/10.1017/S0074180900227290 Published online by Cambridge University Press

or turbulence mixing. The deficiency for temperatures higher than those of the Boesgaard-Tripicco "chasm" is not readily understandable.

The abundance of Zirconium has been studied by M. Smith (1971, 1973) . Its interest comes from the fact that Zirconium reaches a rare gas configuration at the bottom of the convective zone in the stellar mass range under consideration (Michaud *et al.* 1976). However, contrary to the lithium behaviour, Zr is either overabundant or normal, but never underabundant (Fig. 4).

The Aluminium and Iron abundance has been also determined by Burkhart *et al.* (in press) and found to be rather independent of effective temperature and moderately enhanced with respect to normal late-A stars (Fig.4).

4.2 CNO ABUNDANCES

Recently Roby and Lambert (1990) have determined the abundances of the light elements Carbon,Nitrogen and Oxygen in Am and hot Am stars as well

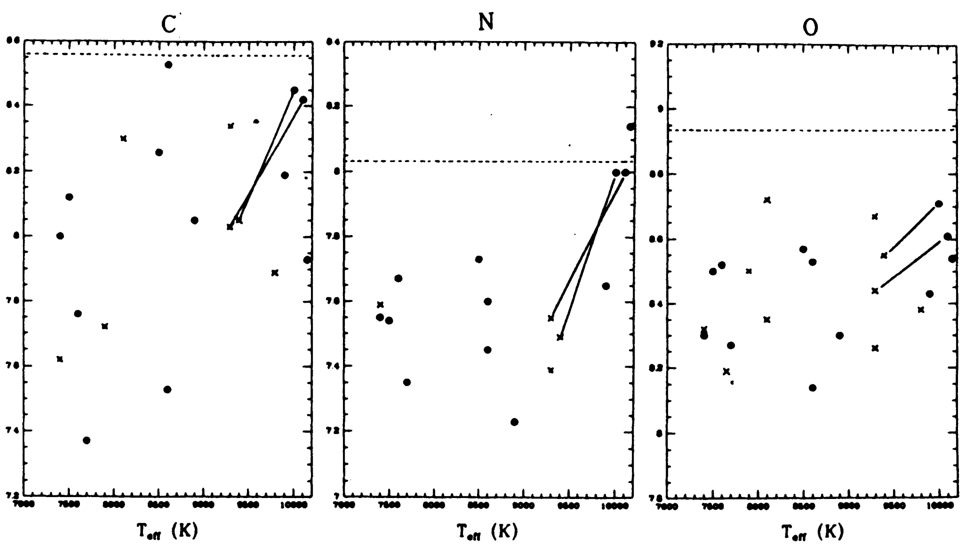

Fig. 5. Abundances of C, N, O elements (scale log NH = 12) as a function of effective temperature. The broken horizontal lines display solar abundances. The results of Roby and Lambert are displayed by filled circles, whereas those of Savanov are given as crosses. Although the results of the two groups are well mixed, the two stars in common (joined by a straight line on the figure) show some systematic discrepancy, partly due to differences in the temperatures used for each star.For C and N there is a tendency to have stronger deficiencies for Fm stars than for hot Am stars.

as in various groups of Ap stars. Their results are shown in Fig. 5 .

Summarizing , the three elements are deficient in Am stars, the deficiency being clearly marked for the coolest Am stars and decreasing to nothing for the hottest one. Similar investigations have been done by Savanov (1988) ,who also finds these elements deficient .
Sadakane and Okyudo(1989) have results in excellent agreement with Roby and Lambert for 3 stars in common. They have also studied the abundance of sulphur and found this element overabundant by 0.5 dex (with respect to the sun) in 68 Tau , and solar abundances in α CMa and ϵ Ser. Adelman and Fuhr (1985) have found O deficient by 0.57 dex, in the hot Am star o Peg.

4.3 RARE-EARTHS

The rare-earths have been reinvestigated with photographic spectra by Van't Veer *et al.* (1988) in the very narrow line Am star HR 178 = HD 3883 . The overabundances found for the rare-earths are of the order of a factor 20 . Quite interesting is the fact that the overabundance factor is very uniform, and preserves the odd-even effect present in the sun and predicted by the theory of the s-process (Clayton and Ward 1974, Cowley and Downs 1980) as shown on Fig. 6 .This uniform overabundance may be explained by diffusion processes of the rare-earth elements which have similar atomic strutures, but theoretical confirmation must wait until detailed radiative acceleration calculations of numerous ions of rare-earths become possible.

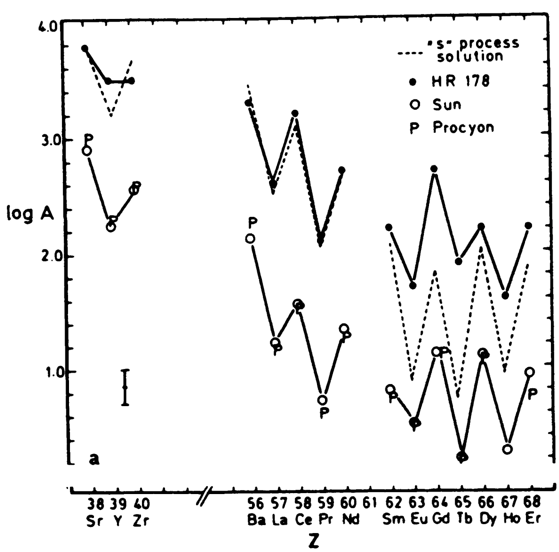

Fig. 6. Sr, Y, Zr, Ba, and rare-earth abundances as a function of the atomic number Z. Solar abundances are those compiled by Grevesse (1984) and Procyon abundances are taken from Kato and Sadakane (1986). Note that the odd-even effect is well preserved in HR 178.

5. Departures from LTE

Although there are little direct quantitative investigations of departures from LTE in metallic-line stars, there is evidence that such departures exist and are far from negligeable. Roby and Lambert(1990) point out a serious discrepancy between temperatures derived from photometry, excitation temperatures from neutral lines, and excitation temperatures from ionized lines in the sample of Am stars they have studied. The problem is not restricted to Am stars but seems to plague all stars in their effective temperature range.

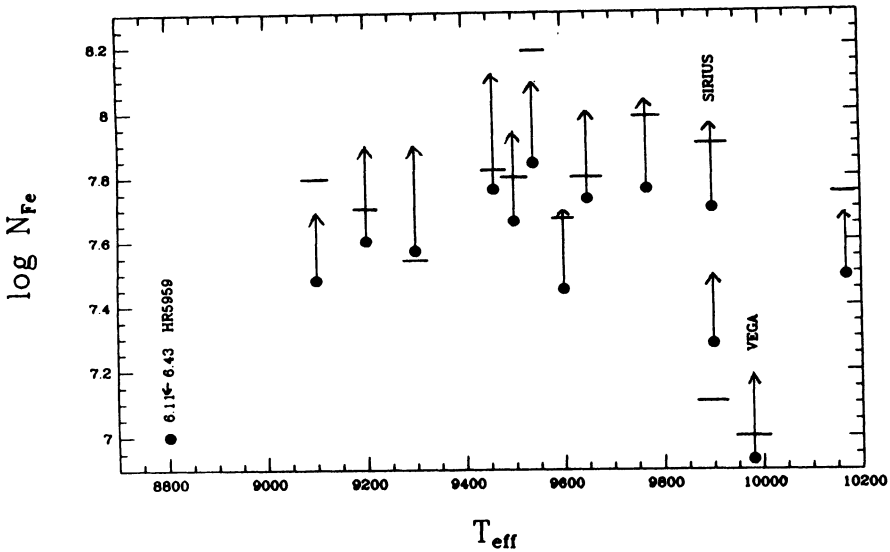

Fig. 7. Departures from LTE in early A stars, according to Lemke (1989). the symbols are as follows: • LTE abundances from Fe I, ^ NLTE abundances from Fe I, – LTE-NLTE (undiscernable) abundances from Fe II.The NLTE corrections amount to 0.2-0.3 dex for Fe I lines, whereas they are unsignificant (0.01-0.03 dex) for ionized lines.

Even at slightly lower effective temperature (6500 K) the thorough detailed analysis of Procyon by Steffen (1985) indicates departures from LTE. Procyon is, with the Sun a rare example of a star for which we know with reasonable accuracy, its effective temperature, mass, radius and metallicity. Steffen notes that the LTE model, with the "true" effective temperature, fails to properly reproduce the ionization equilibria and even the excitation temperature of neutral metallic lines. Everything comes into order, provided the analysis is carried out with a model with a higher effective temperature (indeed higher by 250 K), the resulting chemical composition being then completely solar. It is convincingly advocated that the success of the "wrong" effective temperature is due

to the fact that it cancels, in first approximation, departures from LTE consisting in a slight overionization of iron applying progressively more to deeper neutral lines.
Extra support to this interpretation was given by fully developped non-LTE analyses by Holweger *et al.* (1986), Gigas (1986), Lemke (1989) of hotter A stars, including the two very bright stars Sirius and Vega. We give in Fig. 7 the result found by Lemke for 14 early-A stars including the Am-like star Sirius. The results can be summarized as follows: (i) the abundances derived from ionized iron-lines have negligeable NLTE corrections (ii) the neutral lines have significant corrections of the order of +0.1 to +0.3 dex (LTE abundances too small).Because the Am stars lie in effective temperature just in-between Procyon and the A stars , it appears very likely that they suffer from a similar disease, explaining why most authors, force-fitting the ionization equilibria, have used effective temperatures higher than the "true" effective temperature for 63 Tau.
Our conclusion is that computing departure from LTE is not luxury for Am stars, and that also appropriate models, with the adequate chemical composition and microturbulence and with adequate violet and UV opacities (Kurucz 1990) should be used as soon as possible.These improved opacities are important for fixing the ionizing radiation and consequently departures from LTE .Also the remaining discrepancies between the Lane and Lester (1987) temperatures and the higher temperatures from the IR -flux method should vanish with a new generation of models.

6. Conclusion

New high S/N observations have already allowed to make significant progresses in the knowledge of the abundances of the light elements, Li, C, N, O, Al, S.
Progresses in the abundances of the rare-earths have been made, although still with photographic spectra.
However there is an important body of evidence that these high accuracy new observations cannot be translated into accurate new abundances without a significant improvement on the theoretical treatment of the data. The actual effective temperatures of Am stars are still to be properly determined. The use of Balmer-line profiles and of the I.R. Flux method will allow a significant step forward there.
Departures from LTE must be included in abundance analyses as shown by recent work on normal A and F stars. Before this is done, one can use the "rule of thumb" that ionized lines are not affected by NLTE effects and that neutral lines are better dealt with using a wrong effective temperature about 250 to 300 K higher than the actual effective temperature.
It is not likely that future work will ruin the "classical" anomalies of Am stars: Ca and Sc deficiency, overabundance of iron and still larger overabundance of the rare-earths.

7. Acknowledgements

We are deeply indebted to M.F. Coupry for a fast data reduction of observations of Balmer-line profiles made by R.C.at the Observatoire de Haute Provence in October 1989 and for a continuous help in the preparation of the manuscript, and to C. Megessier for her new determination of the actual effective temperature of 63 Tau.

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