THE ANALYSIS OF CHEMICAL COMPOSITION OF Am STAR ATMOSPHERES

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ABSTRACT. The Survey of principal physical characteristics of the atmospheres of Am stars has been carried out. The anomalies of chemical composition have been discussed. The deficiency in C, O, Mg, Ca, and Sc alongside the excesses of heavier-than-Ni elements, with respect to Fe has been pointed out. The hypothesis on the nature of the observed anomalies are briefly discussed.

1. INTRODUCTION

The "metallic-line" stars are the stars with enhanced lines of metals in their spectra compared to normal stars of the same spectral classes, determined by hydrogen and Ca II lines. They are indicated by the Am index. Naturally, when using common criteria of spectral classification for A stars, they belong to later spectral classes according to the metal lines. Calcium lines are very weak in the spectra of Am stars and therefore spectral classes determined by their intensities are consequently earlier than those determined by the hydrogen lines.

A number of hypotheses have been advanced to explain the anomalies of Am star spectra. Some of them suppose specific conditions of excitation in the atmospheres of Am stars, leading to the observed anomalies. Other hypotheses assume that we deal with real anomalies in the chemical composition of the atmospheres of Am stars.

By now more than 40 Am stars have been studied on the basis of spectrograms with dispersion better than 10A/mm. The analysis has been facilitated using model atmospheres. The majority of stars was analyzed by Smith (1971, 1973, 1974), Conti (1965, 1970), and Conti and Strom (1968), and in the Crimea by Lyubimkov and Savanov (1983). Many other astronomers analyzed no more than one star. As a result we obtained the material involving a great number of stars distributed over a wide range of effective temperatures thus making it possible to establish correlations and general laws concerning spectral anomalies of Am stars. However, it should be noted, that the data available for Am stars are imperfect. First, different authors used as standards various stars, that might lead to additional inhomogeneity of the material. Second, the most extended analyses of spectrograms have been carried out with obsolete values of oscillator strengths.

2. PHYSICAL CONDITIONS IN THE ATMOSPHERES OF Am STARS

By using model atmospheres it is possible to estimate the effective temperature, T_{eff}, the surface gravity g and the value of the turbulent velocity V_t. For this aim the following criteria should be used: hydrogen line profiles, estimates of ionization equilibrium and energy distributions in narrow spectral regions determined by scanner observations as well as narrow band photometry.

Figure 1 shows the position of Am stars on the diagram log(g)-T_{eff}. One can see that

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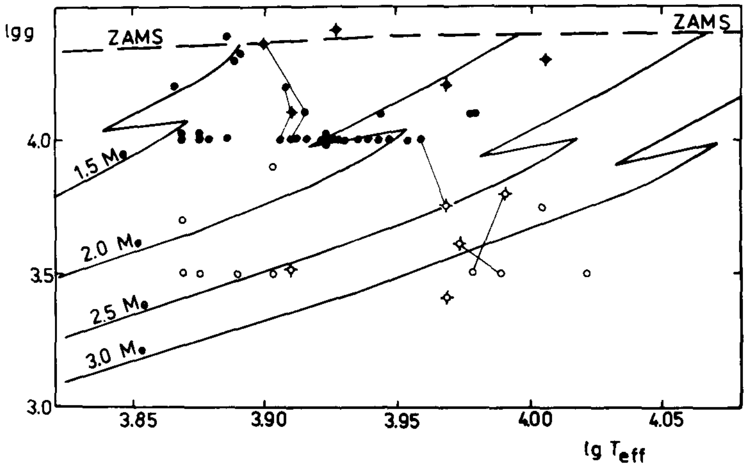

Figure 1. The location of Am stars on the diagram of log(g)-T_{eff}. Evolutionary tracks are from Mengel et al. (1979). Open circles correspond to the evolved stars—filled ones to the unevolved. Circles with crosses stand for the stars studied in the Crimea. Lines connect the results obtained by different authors for the same star.

Am stars have the effective temperatures in the range from 7400 to about 10000K, that fall within the range of spectral classes B9 - F0. The low temperature limit for Am stars is probably reliable. A special search for cool Am stars has been carried out (Smith 1973). In the spectra of F0 stars and cooler, Sc, Ca and Fe lines are intensive enough and the existence of anomalies between their intensities might be easily found. As far as the high temperature range of Am stars distribution is concerned, the situation is less reliable. The matter is that due to the increase of the level of ionization, the Sc. Ca, and metallic lines noticeably weaken and after that completely disappear. Probably in the future the UV data analysis of Sc III and Ca III lines would clarify this phenomenon, but spectral anomalies can be discovered only by quantitative analysis of high dispersion spectrograms. Thus Boyarchuk (1963) has found that the brightest star α CMa is an Am star and Smith (1974) showed that the star θ Leo, which was believed to be the standard for spectral classification is also an Am star.

The values of microturbulent velocities in the atmospheres of Am and A stars are almost the same. Such conclusions were drawn earlier by Baschek and Reimers (1969) and Smith (1971). They have also remarked, that for the stars with the effective temperature from 7600 to 9000K, the microturbulent velocity is higher than for the adjacent regions. Recently the assumption of modern values of oscillator strengths and blanketing and the account on the superfine structure resulted in the fact that the value of the turbulent velocity for the Sun considerably decreased from 2 km/s to 0.8 - 1.0 km/s. However, since the atmospheres of Am and A stars have been analyzed by the same method the conclusion that in the atmospheres of Am and A stars the turbulent velocities are equal, probably remains reliable. Modern model atmospheres being applied for Am stars has shown that to determine the relative intensities of lines and their profiles, no sophistication of the model with respect to the model of normal stars is needed. Particularly, low electron density on the surface of a star is not necessary.

Furthermore, according to modern methods of analysis, it might be concluded that the atmospheres of Am and A stars are similar by their physical parameters, and anomalous relations between line intensities observed in the spectra of Am stars shouldn't be ascribed to the effects of excitation.

Finally, we remark that the rotational velocity of Am stars is considerably lower than that of A stars. Metallicism may occur at the stars with v•sin(i) up to the value of 60 - 70 km/s (like in β Ari, cf. Mitton 1977).

3. CHEMICAL COMPOSITION OF THE ATMOSPHERES OF Am STARS.

As stated above, the anomalous relations of line intensities in Am star spectra shouldn't be ascribed to excitation potentials. Therefore we assume that these anomalies are connected with the anomalous abundances of Am stars.

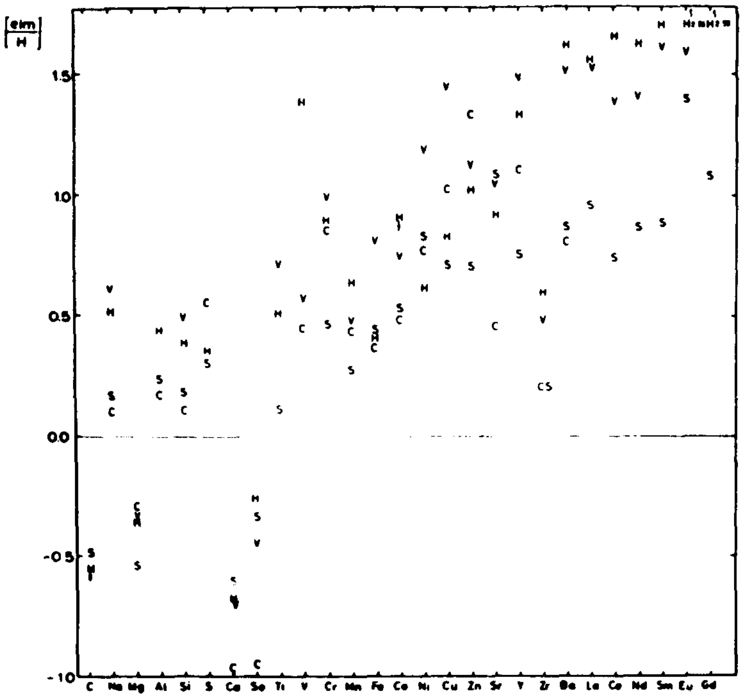

Figure 2. The abundance anomalies of the atmosphere of the star 63 Tau, determined by different authors. H stands for Hund (1972), V is for van't Veer-Menneret (1963), C is for Conti (1965), and S is for Smith (1976).

Hereafter, we use the following conventional notation:

$$[Fe/H] \equiv \log (N(Fe)/N(H))_{Am} - \log (N(Fe)/N(H))_{Std\ star}$$

So, we obtain the data on chemical compositions of the atmospheres available for more than 40 Am stars. Unfortunately, different authors used different values of oscillator strengths and different standard stars, that might led to the discrepancy of data. As an example, Figure 2 shows the values of element-to-hydrogen with respect to the atomic number, for 63 Tau. One can see that the discrepancy here is rather high. With due regard for the specific determination of the comparison of different elements, let us consider the abundance of different elements relative to iron, and separately the abundance of Fe relative to hydrogen. We readily assume, that such comparative methods would help to eliminate the contribution of errors. Figure 3 demonstrates relative abundances of elements in the atmospheres of Am stars.

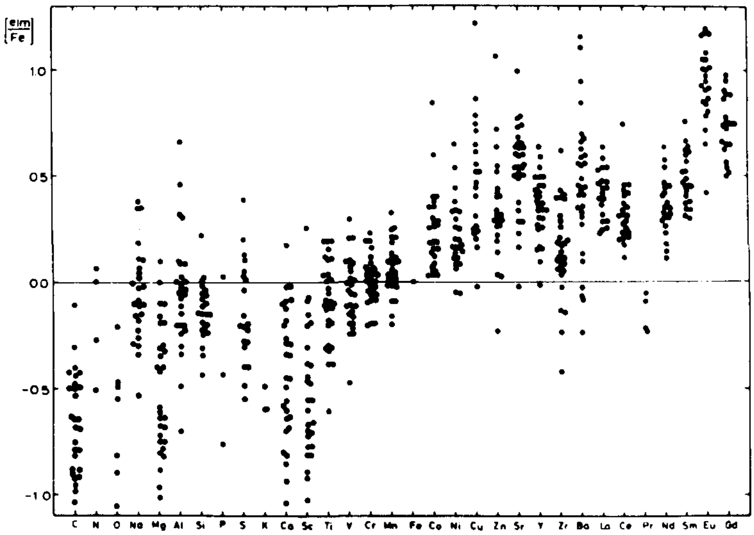

Figure 3. Relative abundance of the elements in the atmospheres of the Am stars (see the text).

According to Figure 3, one can draw the following conclusions:

1) While passing from light elements to heavier ones the excesses of elements increases.
2) The increase of overabundance of elements is not monotonic. Among light elements, the deficiency of C, O, Mg, and Ca, Sc is obvious, but at the same time Na, Al and probably Si and S are of normal content. Among heavier elements there is a great excess of Sr, Ba, Eu, and Gd together with moderate excesses of Zr, Ce, and Nd. More precise consideration of Eu content also evidences for its excess by 10 times (Hartoog and Cowley 1974).
3) The scatter is rather high for all elements than the elements of the Fe group. The abundance of these elements are determined by a great number of lines and the errors are not appreciable. But for other elements the scatter exceeds an order of magnitude: Ba, for instance. From several general considerations we proceed to the analysis of the results obtained for separate elements. Here we shall deal with the data obtained by high dispersion spectrograms with blanketing model atmospheres reduced to the same scale of oscillator strengths.

Figure 4 shows the abundance of iron in the atmospheres of Am stars with respect to that in the atmospheres of standard A stars. The iron abundance in the atmospheres of Am stars turns out to be thrice that in the normal star's atmospheres. There is a weak tendency in the atmospheres of hotter Am stars to have greater excess of Fe, than in cooler stars.

For some elements which are not presented in Fig. 3, we obtain some qualitative data.

Wallerstein and Conti (1969) haven't found any Li or Be lines in the spectra of Am stars, this fact testifies that there is no great excess of these elements. Boesgaard and Praderie

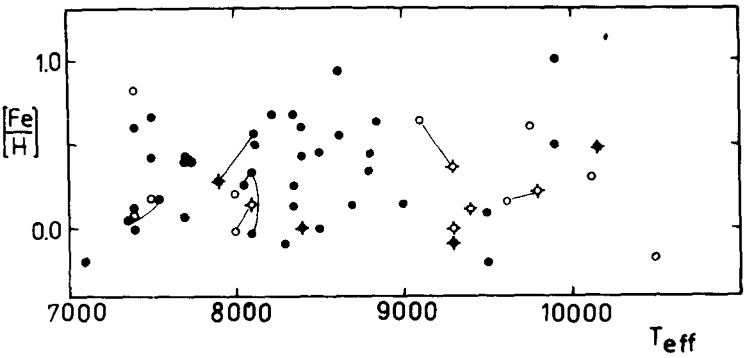

Figure 4. Abundances of iron as a function of the effective temperature. Signs are the same as in Fig. 1.

(1981) obtained later, that Be and B are greatly underabundant in the atmospheres of α CMa and γ Gem. Smith (1974) found that the He abundance in three stars, θ Leo, α GemA and α CMa is about twice as low. Boyarchuk and Show (1978) haven't found any Tc, Pt, and Hg in the ultraviolet spectra of α CMa obtained with the Copernicus satellite with 0.05 and 0.1A spectral resolution. Cowley, Aikman, and Hartoog (1976) haven't found any evidence for actinides. Lyubmikov and Savanov (1985) found strong excesses of Th in the atmospheres of Am stars: 15 Vul, 16 Ori, 63 Tau, and no excess in the atmosphere of 81 Tau.

It is interesting to consider the correlations between abundance anomalies of different elements. Figure 5 shows the comparison of the values of [Ca/Fe] and [Sc/Fe]. There is a good correlation between the anomalies of Ca and Sc abundances. Such a correlation also exists between [Ca/Fe] and [Mg/Fe]. However, the correlation between [C/Fe] and [Ca/Fe] is practically absent.

The dependence of [Ca/Fe] on the effective temperature is quite weak (see Figure 6), i.e. cooler stars may have more deficiencies of Ca. There is almost no correlation between [C/Fe] and T_{eff} values. Insofar, the anomalies of C are to some extent different than the ones of Mg, Ca, and Sc.

The anomalies of heavy elements probably also correlate with each other (with insignificant exceptions), but since the scatter is rather high, a definite conclusion is hard to draw. Following Figure 7, one can observe substantial correlations between [La/Fe] and [Nd/Fe]. On the other hand, according to Figure 8, there is no reliable correlation between [Zr/Fe] and [Ba/Fe].

But taking into account Figure 9, one cannot see a tendency of the value [Zr/Ba] to depend on the effective temperature.

There is no strong correlation between the value of the deficiency in light elements and the excess of heavy ones, e.g. between [C/Fe] and [Eu/Fe]. the lower the rotational velocity of the star, the stronger the anomalies of chemical composition. Kodaira (1976) found that

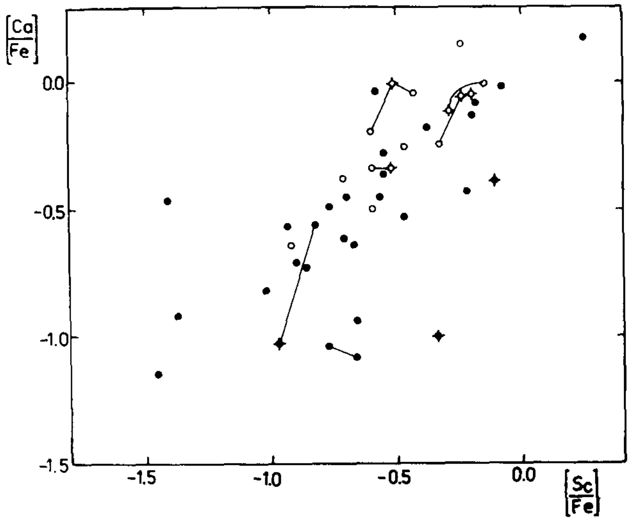

Figure 5. The comparison between the abundance anomalies of Ca and Sc. Signs are the same as in Fig. 1.

metallicity index $[m_1]$ decreases with the increase of v•sin(i). Correlations of the abundances with rotation were studied by Smith (1973). We consider the dependence of [V/H] on v•sin(i) for evolved and unevolved stars (a) and "hot" and "cool" Am stars (b), as shown in Figure 10.

Significant scatter on the presented figures involves difficulties for conclusions, and makes them less reliable. But, some qualitative conclusions are likely possible:

1) The peculiarity of chemical abundance of Am star atmospheres is the excess of heavy elements increasing on the average with the atomic weight. The deficiency of several light elements has been found.
2) In some cases the correlations between anomalies exist, in other cases they vanish. At present, due to insufficient accuracy, we are not apt to make any definite remarks.

To make these conclusions more well founded, more accurate and homogeneous data on the chemical composition of the atmospheres of Am stars are needed.

4. THE ORIGIN OF CHEMICAL COMPOSITION ANOMALIES

As it was stated above, the detailed analysis of the spectra of Am stars showed, that the anomalies in correlations between line intensities of different elements should not be ascribed to some specific conditions of excitation, and we deal with real anomalies of chemical composition.

The existing hypotheses on the nature of anomalies can be provisionally divided into two groups.

According to the first group, chemical anomalies are formed outside the stars, primarily in different types of accretion, where the separation or formation of chemical composition

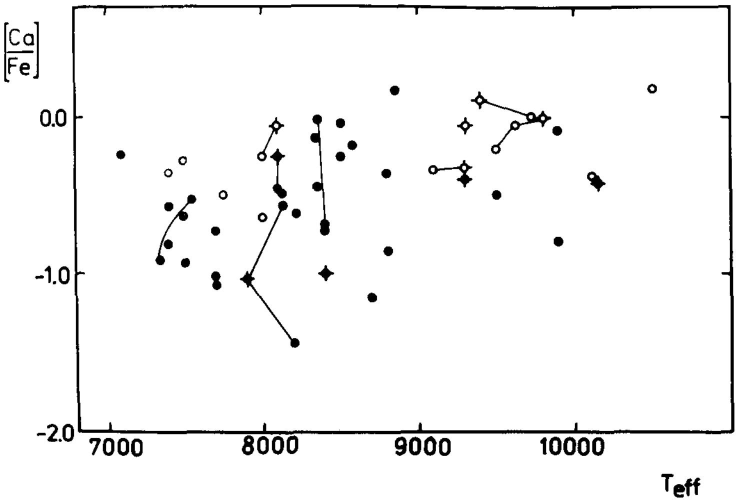

Figure 6. Abundance of calcium as a function of the effective temperature. Signs are the same as in Figure 1.

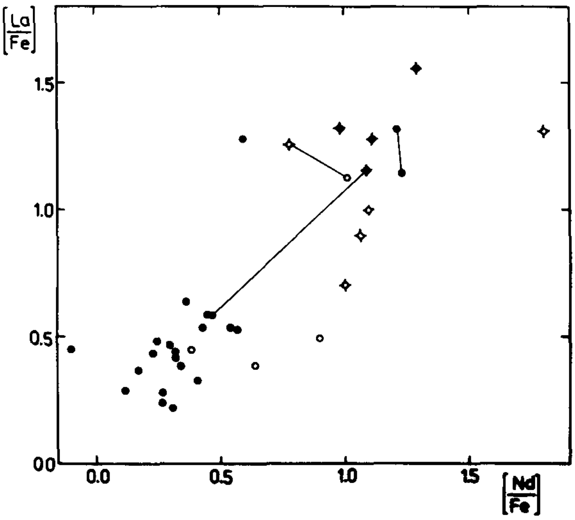

Figure 7. The comparison between the abundance anomalies of [La/Fe] and [Nd/Fe]. Signs are the same as in Figure 1.

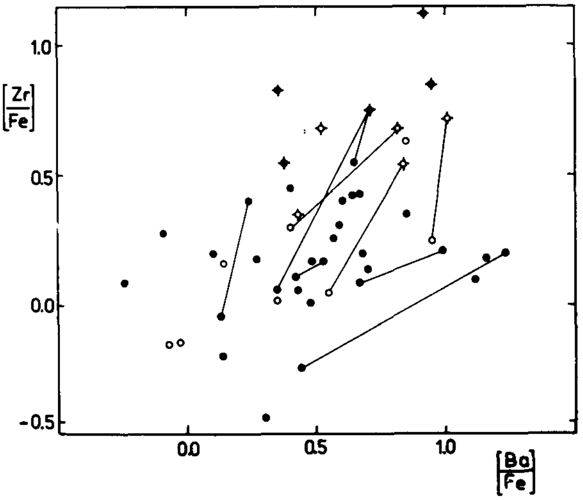

Figure 8. The comparison between the abundance anomalies of [Zr/Fe] and [Ba/Fe]. Signs are the same as in Figure 1.

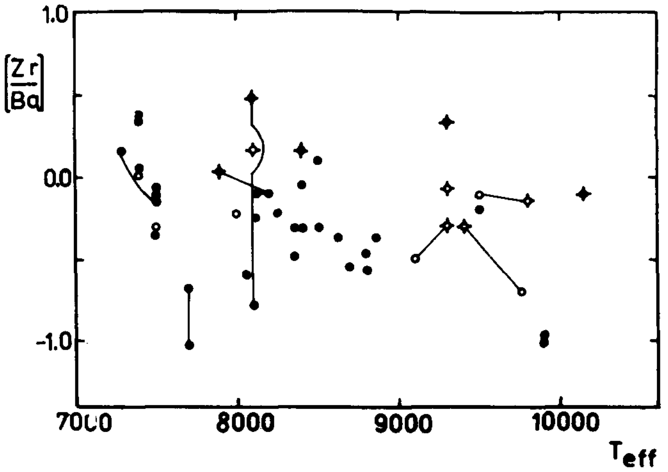

Figure 9. The dependence of [Zr/Ba] values on the effective temperature. Signs are the same as in Figure 1.

depends either on the magnetic field influence or by matter outflow in the binary system. It is noteworthy, that these initial hypotheses transform the problem of chemical composition in the

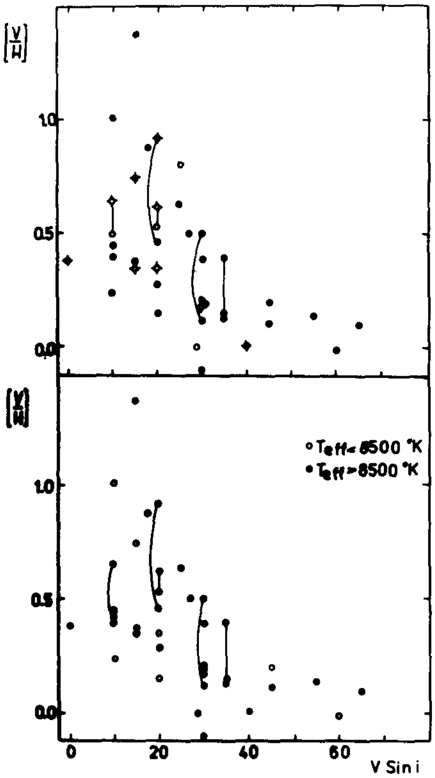

Figure 10. The comparison between [V/H] and rotational velocity for: evolved and unevolved stars (above), and "hot" and "cool" Am stars (below).

atmospheres of Am stars into two problems: formation of the elements outside the star, and matter transfer on the surface of the "metallic" star. The theories of this trend come across such difficulties are, for example, the interpretation of the presence of Am stars in young clusters and the absence of strong magnetic fields in the Am stars.

Other hypotheses ascribe the formation of chemical composition anomalies to the processes in the interior of stars, for instance, mixing processes, where the upper layers are enriched with heavy elements. In spite of numerous obstacles, this theory is advantageous to explain the presence of heavy elements in the atmospheres of "metallic" line stars. Probably the most promising is the hypothesis on diffusive separation of elements by radiation pressure. However, this hypothesis needs to consider not only the behavior of separate elements, but to extrapolate it to the abundances of different elements in total.

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