A SEARCH FOR HEAVY ELEMENTS IN THE ULTRAVIOLET SPECTRA OF Ap STARS

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ABSTRACT. The earlier attempts to detect the lines of heavy elements (Pb, U, Th and others) in the spectra of Ap-stars from the ground-based observations are briefly discussed. UV observations of Ap-stars with the ultraviolet telescope aboard ASTRON space station are described. The reduction of these data is considered. Three spectral regions containing the lines PbIIλ2203.53, UII λ2556.19 and ThII λ2368.05 were analyzed by the method of synthetic spectra. It has been shown that relatively cool Ap-star 73 Dra (T_{eff}=8150 K) has a great overabundance ($\geqslant 10^3 \varepsilon_\odot$) of heavy elements U, Th, Pb and W.

1. EARLIER IDENTIFICATIONS OF HEAVY ELEMENTS' LINES FROM THE GROUND-BASED OBSERVATIONS

Attempts have been made to determine the abundance of lead from visible spectra of stars all turned to be inconclusive. The line λ 5042.5 suspected by Burbidges (1955) as Pb-line in the spectrum of α^2CVn turned out to be wrong (Cohen et al. (1959)), as the other lines of Pb were absent in the spectrum of this star. The attempts of Guthrie (1972) to do the same with the line λ 4157.81 were unreliable because he arbitrarily assumed Os abundance to be 10^3. Besides, this line is strongly blended with the lines of FeII and MgI, and the estimates were based on the curve-of-growth analysis with rather arbitrary assumptions about the atmospheric structure (the osmium abundance is also

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very uncertain). The Wegner and Petford (1974) estimates based on three weak, high excitation lines in Pzybilski star HD 10165, was "very shaky" as the authors concluded, because of the unreliability of the oscillator strengths.

Studying Os lines in 73 Dra, Guthrie (1969) suspected that UII-lines ($\lambda\lambda$4241.67 and 4543.63) were present. There appeared several other papers on the possible presence of U-lines in the visible spectrum of this star. Jashek and Malaroda (1970) found seven Pt-lines, four AuI-lines and five UII-lines. These authors were the first to note that the presence of these elements is difficult to be reconciled with the theory of Fowler et al. (1967) speculating that Ap-stars evolve after the red-giant phase: the presence of these elements (formed via r-process) on the surface of the stars requires the material of the star to have, at some time, been subjected to conditions that exist in stellar interiors only (these elements may also be formed at the explosion of a companion star).

Soon after that Brandi and Jashek (1970) found some traces of OsI, OsII, PtII and UII in five out of twelve stars. In particular, they called attention to a strong line λ 3860 identified as UII. This identification was confirmed by Hardorp and Shore (1971). The latters were able to identify except λ 3860, also $\lambda\lambda$4091 and 4242 lines as UII-lines in the spectrum of βCr B. Later Jashek and Brandi (1972) reported the identification of ThII, UII and AmII in the spectrum of the Ap-star HD 25354 (Sp-variable with $P=3\overset{d}{.}9$). They were also first to report the detection of a WI-line.

Hartoog and Cowley (1972) reported the identification of UII in the spectrum of HR 465 and a little later Cowley and Hartoog (1972) reported the U-abundance in this star about 10^6 times of the solar system abundance (at a significance level 3.8σ). The presence of UII-lines in βCrB was once again confirmed by Adelman and Shore (1973) at 4 sigma level. The line λ4019.13 of ThII may be present in stars HD 18078, 81009 and 165474. The UII-line λ 3859.58 is possibly present in 20 out of 21 star studied by Adelman (1973), while UII-line λ 4241.67 may be present in six of them. Adelman believes, that UII identification is not definite - more accurate measures of $\lambda\lambda$ 3860 and 4242 lines are needed. Seventy four elements have been identified for five Ap-stars (β CrB, 73 Dra, 78 Vir, HR 4816, HR 4072) using wavelength coincidence method (Cowley, Hartoog and Cowley, 1974). These authors concluded that only one heavy element, Pt, is identified with high confidence in HR 4072, while UII may be present in 73 Dra and β CrB; OsII may be present in β CrB. However the identification of UII is based mainly on λ 3859.58 line which is obviously present in the spectrum, while the λ 4241.67 line yeilds no definite indications. As for the other stars, there was no clear evidence for the presence of UII or ThII lines.

As far as the ultraviolet spectra of Ap-stars is concerned, there are still very few investigations aimed at the search for heavy elements (for instance, see the review of Castelli et al., 1983). Our investigations are based on the UV spectra of Ap-stars obtained with ultraviolet telescope aboard ASTRON space station.

2. "ASTRON" OBSERVATIONS IN THE ULTRAVIOLET

Space station ASTRON is equipped with 80-cm Cassegrain reflecting telescope having 8-m equivalent focal length and the X-ray sensors. The station was launched on highly elliptical orbit with apogee 200×10^3 km and perigee 2×10^3 km. Such an orbit is advantageous for avoiding the radiation belts influence on the photoelectric recordings of stellar spectra which are made near the apogee. Being launched in March 1983, ASTRON is still in operation.

The spectra are obtained with the concave toroidal grating and recorded by photoelectric scanning along the Rowland circle. Star pointing is realized by a slight inclination of secondary convex (hyperbolic) mirror as an element of guiding system. There exist two guiding systems: 1) by using the eccentricity of position of star image in question on the slit jaws and for weaker stars 2) the

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off-set system, where other bright stars in the vicinity of the star in question are used ($\leq$ 10' from a given star). More detailed description of ASTRON space telescope is given by Boyarchuk et al. (1984).

TABLE I. SPECTRAL LINES IN UV REGION

Element	Line	Z	A	$\log \varepsilon_c$	$\log \varepsilon_\odot$
PbII	2203.53	82	204,206,207,208	1.78	1.9
ThII	2368.05	90	232	0.7	0.2
UII	2556.19	92	238,235	0.0	<0.6

In the present work based on the analysis of ASTRON observations a search for heavy elements (lead, uranium and thorium) was carried out for several Ap-stars. The observed spectra were obtained by scanning the limited spectral ranges ± 2.5 Å wide centered on the wavelengths given in Table I, where Z and A are the atomic number and atomic weight, $\log \varepsilon_c$ is the cosmic abundance according to Allen (1973), $\log \varepsilon_\odot$ is the solar abundance after Hauge and Engvold (1977). The log ε values are given in the scale where the hydrogen abundance log ε (H) equals to 12.00.

Eleven Ap-stars were observed: $\varkappa$ Cnc, 15 Cnc, 78 Vir, ι Lib, 73 Dra, 9 ω Oph, 21 Per, 41 Tau, 21 Aql, 53 Tau and β CrB. It was shown recently by Adelman (1984) that 21 Aql is a normal star of spectral type B7 IV. Only three Ap-stars of the remaining ten stars have been subjected to a detailed analysis so far: 73 Dra(T_{eff}=8150 K), 9 ω Oph (T_{eff}=9500 K) and $\varkappa$ Cnc(T_{eff}=13600 K). The normal star λ UMa was investigated also to examine the oscillator strengths of lines in the spectral intervals under consideration.

The profile of each 5 Å interval was recorded with a small entrance slit aperture equal to 1" (accuracy of pointing being $\pm 0''.3$) and narrow exit slit (resolution equal to 0.4 Å). The intensity was determined in relative units of the total wideband (28 Å-wide), relative to the intensity in the first ("comparison") channel, to remove possible influences of instabilities in the position of the star on the entrance aperture *). At each scanner position (fixed wavelength) 180 separate estimates were obtained (that corresponds to $1^m.83$ integration time). The dark current was recorded during the intervals between scans ($\sim 2^m$). (The total time required for one spectrum registration is a little more than 3 hours corresponding to six successive scans). In order to reduce more than 180x16=2880 measures (each section of the spectrum is 5 Å wide) a reasonable data reduction program should be provided for our computer, which is adopted to magnetic tapes obtained from the tracking station.

Clipping procedure is roughly as follows: all counts are reduced for dark current (d.c.) and all values of count numbers N_2 and N_1 smaller than fluctuations in d.c. ($\simeq \sqrt{d.c.}$) are eliminated. So after the first reduction we have the number of points M_1 with the mean value A_1 and r.m.s. deviation σ_0. After

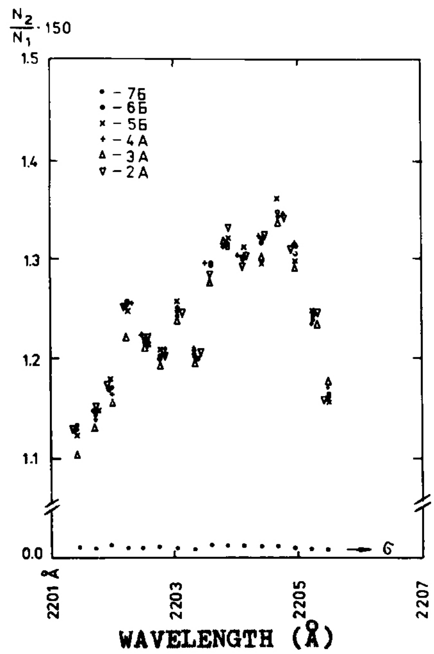

Figure 1

An example of using different data reduction programs to ASTRON observations in PbII section. N_1 and N_2 are number of counts in the first and second channels.

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*) I.E. the average of $\Sigma(N_2/N_1)$ or $\Sigma N_2 / \Sigma N_1$ was determined for each scanner position; here N1 and N2-numbers of counts in the first and in the second channels.

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that all the points deviated from the mean $\geq 5\sigma_0$ are thrown away. This gives a new data set M_2 with the mean value A_2 and r.m.s. deviation σ_1. Then again all points with r.m.s. deviations $\geq 4\sigma_1$ are eliminated,and so on until we reach data sets M_5 and M_6 after throwing away the points beyond the $1\sigma_4$ and $1/2\sigma_5$ levels. The final data contains about 1500 points, which corresponds to about 60% of the original number.

From Fig. 1 it is clear that different programs of reduction yeild virtually identical results.

Further analysis are based on the comparison of the observed spectra in the considered UV regions with the synthetic spectra calculated for the same section of spectrum. The computer program SYNTHEL was applied in which the star rotation and the instrumental profile are taken into account. The list of spectral lines was selected from the table of Kurucz and Peytremann (1975). For the most UV lines this table is the only source of oscillator strengths gf. It is known that for some lines the semiempirical gf-values of Kurucz and Peytremann may contain significant errors. For the refinement of gf-values we analyzed at first ASTRON spectra of the normal star λ UMa with a known chemical composition. The adopted values of the effective temperature T_{eff}, surface gravity g and rotational velocity $v \sin i$ for λ UMa and for three Ap-stars investigated in detail are given in Table II. To determine the parameters T_{eff} and log g, we used

TABLE II. EFFECTIVE TEMPERATURES, SURFACE GRAVITIES AND ROTATIONAL VELOCITIES OF FOUR INVESTIGATED STARS

Star	Type	T_{eff}	log g	$v \sin i$ (km/s)
λ UMa	A2 IV	9300	3.7	45
73 Dra	Sr-Cr-Eu	8150	3.6	9
9 ω Oph	Sr-(Cr)	9500	4.0	35
æ Cnc	Mn-Hg	13600	3.6	6

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the following features of visible spectrum: Balmer line profiles, $[C_1]$-index in uvby-system, and correspondence in iron abundance between FeI and FeII lines (ionization equilibrium).

The synthetic spectra were convoluted with rotation and with instrumental profile of ASTRON spectrometer (resolution is 0.4 Å). To establish the position of the observed continuum we calibrated from synthetic spectrum a rest intensity of some strong blends in the considered spectral sections (other than blends containing PbII, ThII or UII lines). The influence of scattered light on the observed profiles is negligible, less than 2% according to special investigation of A.A. Boyarchuk.

At first we consider the results of lead abundance determinations from the PbII-line λ 2203.53. This line has an excitation potential of lower level χ = 1.73 eV and oscillator strength log gf = -0.15 (Kunisz and Migdalek, 1974). It is blended with the MnII-line λ 2203.52 (χ = 4.5 eV) and with highly excited lines NiII λ 2203.47 (χ = 7.0 eV) and CrIII λ 2203.27 (χ=7.9eV). Two latter lines are not important for relatively cool Ap-stars (e.g. for 73 Dra), but in the spectra of hotter stars the contribution of NiII λ 2203.47 may be more considerable. The role of NiII line proved to be especially significant in the case of $\varkappa$ Cnc. The preliminary analysis of PbII-section for this star was carried out with nickel relative abundance [Ni] = $\log \varepsilon(\mathrm{Ni})_* - \log \varepsilon(\mathrm{Ni})_\odot$ = -1.0 obtained by Leckrone (1981) from UV spectrum of $\varkappa$ Cnc. For such Ni deficiency the lead overabundance [Pb] = 1.8 in $\varkappa$ Cnc has been found (Boyarchuk et al., 1984). But from the study of visible spectrum of this star follows, that Ni abundance is more close to solar value (Aller, 1970; Heacox, 1979). Our calculations showed that in this case the uncertainty in Ni abundance proves more important than variation in Pb abundance. Therefore it is difficult to obtain a reliable estimation of the lead content in this high temperature star.

In case of cooler Ap-star 9 ω Oph a synthetic spectrum is more sensitive to Pb abundance. A preliminary analysis of the visual spectrum shows that [Fe] = 0.3, [Mn] = 1.2 and [Cr] = 1.2. For these values and at normal Pb abundance we obtain a good agreement between the observed and synthetic spectra of this star if nickel abundance is normal, too. From the line WII λ2204.48 being in the same spectral section, we derived for 9ωOph tungsten overabundance [W] = 1.2.

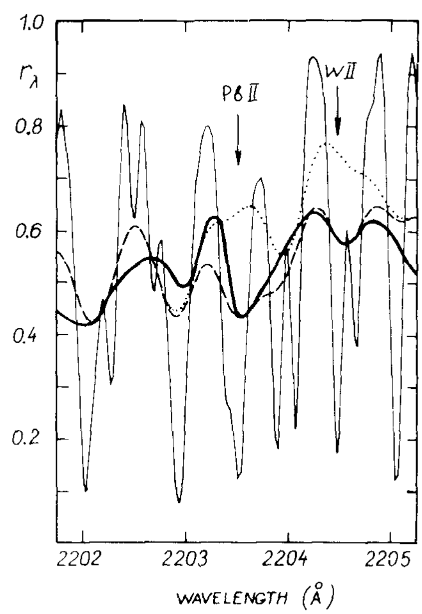
Of three investigated Ap-stars, 73 Dra is the coolest. At first we used for it the model atmosphere of Sadakane (1976) with parameters T_{eff} = 8900 K and log g = 3.9. But later its visual spectrum was totally reanalyzed (Lyubimkov, in press), that allowed to conclude that the effective temperature of 73 Dra is considerably lower (see Table II). Such temperature decrease for this star has especially great importance for U abundance determination (see below).

Figure 2.

Comparison of the observed and computed spectra of 73 Dra in the section of PbII λ2203.53 and WII λ2204.48 lines. Thin line corresponds to synthetic spectrum convoluted with rotation, dotted and dashed indicate convolution also with instrumental profile (for normal and enhanced abundance of heavy elements analyzed : Pb and W).

ASTRON spectrum ———

Synthetic spectrum:
log ε(Pb)=5.4, log ε(W)=3.6 – – –
log ε(Pb)=1.9, log ε(W)=0.8 ········



On Figure 2 the comparison of the computed and observed spectra of 73 Dra in PbII-section is shown. Calculations were made for a chemical composition found from visual region. If we take a normal Pb and W abundances (dotted line) a great dis-

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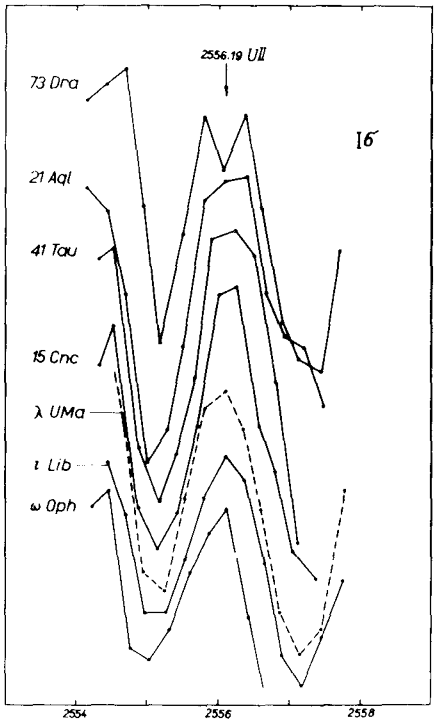


Figure 3.

ASTRON spectra of some program stars in the section of the line UII λ 2556.19. The intensities are given in relative units; the curves of different stars are shifted relative to each other.

crepancy arises between theoretical and observed spectra. A good fit to ASTRON spectrum may be obtained only for considerable Pb and W overabundance : log ε(Pb) = 5.4 and log ε(W) = 3.6, i.e. [Pb] = 3.5 and [W] = 2.8 (dashed line).

Now let us consider ASTRON observations of UII-section. Of eleven Ap-stars only for 73 Dra a clear depression exceeding 3 sigma is visible at the place of UII λ 2556.19 (Figure 3). This star has been observed twice - in 1983 and 1984 at the same phase φ = 0.77, and the depression appeared to be on both spectra. The line UII λ 2556.19 is blended with the lines TiII λ 2555.98 and MnII λ 2556.57. Relative contribution of the two lines depends on adopted effective temperature T_{eff}. Using Sadakane (1976) model atmosphere with T_{eff} = 8900 K, we have found enormously high uranium overabundance [U] > 5.0 (the oscillator strength log gf = -1.14 was adopted for the line UII λ 2556.19 according to Corliss, 1976). But from the improved model atmosphere with lower temperature T_{eff} = 8150 K we obtained more moderate U overabundance.

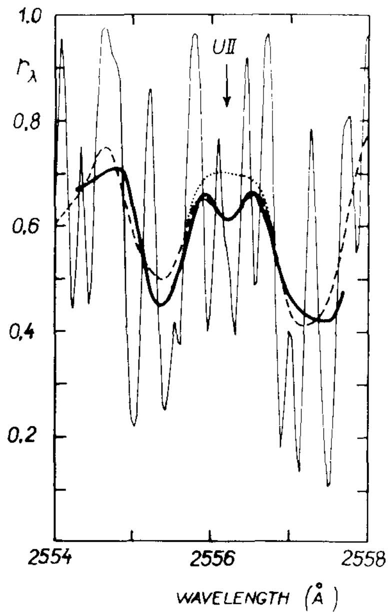
Figure 4 shows that a good fit to the observed spectrum of 73 Dra is reached for log ε (U) = 4.4, i.e. for [U] ≥ 3.8. It is interesting to note that for normal U-abundance the depression on 2556.2 Å is absolutely absent in the computed spectra (dotted line in Figure 4).

Figure 4.

Comparison of the observed and computed spectra of 73 Dra in the section of the line UII λ 2556.19 (additional explanations see in Fig. 2).

ASTRON spectrum ———

Synthetic spectrum:
log ε (U) = 4.4 – – –
log ε (U) = 0.6 ·······



In order to confirm the value of log ε (U) derived from ASTRON spectrum, we consider also the line UII λ 3859.58 in the visible region of the spectrum. The oscillator strength of this line is log gf = −0.62 according to Voigt (1975). It is important to note that for both UII λ 3859.58 and UII λ 2556.19 the adopted gf-values correspond to the same scale of Voigt. The visual spectra of 73 Dra in the region considered were obtained by Cowley et al. (1977) and recently by Iliev (unpublished) at the Bulgarian National Astronomical Observatory (BNAO). In the latter case the phase φ = 0.88 was close to the phase of

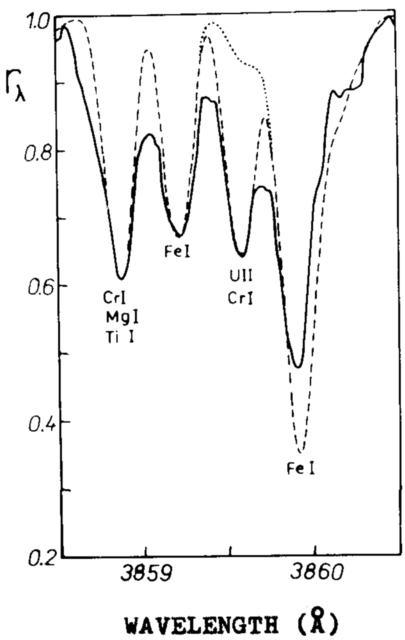
ASTRON observations. By comparing the BNAO and synthetic spectra in the region of UII λ3859.58 (see Figure 5), the value of log ε (U) = 3.9 has been determined, which differed by 0.5 from the ASTRON value log ε (U) = 4.4. This difference corresponds just to ASTRON error of observations σ, which is indicated in Figure 3.

Figure 5.

Comparison of the observed and computed spectra of 73 Dra in the section of the line UII λ3859.58 (additional explanation see in Fig. 2).

BNAO spectrum ———

Synthetic spectrum:
log ε(U) = 3.9 – – –
log ε(U) = 0.6 ....



Two DAO spectra (Cowley et al., 1977) obtained in two different phases have been also analyzed.

TABLE III. URANIUM ABUNDANCE IN 73 Dra DERIVED FROM VISIBLE AND UV-SPECTRA

Phase	UII-line	Spectrum	log ε(U)
0.19	3859.58	DAO	3.6
0.54	3859.58	DAO	3.2
0.77	2556.19	ASTRON	4.4
0.88	3859.58	BNAO	3.9

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Table III shows that DAO spectra yeild lower values of log ε(U) than found from BNAO or ASTRON spectra, especially at the phase φ = 0.54. At this phase the extraordinary weakness of FeI lines has beenalso marked by Cowley et al. (1977). The difference in U abundances according to the data obtained at several observatories may be connected with real UII-line variations depending on the phase φ (such periodical variations of some lines in the spectrum of 73 Dra are well known). Further observations of UII λ 3859.58 are needed to solve this problem.

We conclude that great overabundance of uranium follows from visible and ultraviolet data on 73 Dra. As can be seen from Table III, the mean value is log ε (U) = 3.8, i.e. [U]$\geqslant$3.2. That is in good agreement with the overabundance of lead [Pb] = 3.5 and tungsten [W] = 2.8 found by us for 73 Dra from PbII-section.

Relatively cool Ap-stars (such as 73 Dra) are more suitable for a detection of the line UII λ2556.19. Our calculations showed that for the relatively hot peculiar star 53 Tau (T_{eff}= 12000 K) a marked depression at λ 2556.19 may appear only for great overabundance of uranium [U]>4.0.

Finally we mention the results concerning ASTRON observation of ThII-section. Clear depression at the place of ThII λ 2368.05 line is visible for 73 Dra. Preliminary analysis suggests that the thorium abundance in this star is also high, $\geqslant 10^3$ of the solar value. Therefore we can conclude that the investigations of Ap-star 73 Dra based on ASTRON ultraviolet spectra indicate high ($\geqslant 10^3 \varepsilon_{\odot}$) content of heavy elements, such as uranium, thorium, lead and tungsten .

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Discussion appears after the following paper.