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A SURVEY OF PECULIAR AND METALLIC-LINED A STARS FOR THE ACTINIDES*

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ABSTRACT

In a high-dispersion survey using modern wavelength lists, we have failed to find convincing evidence for any transuranic actinide in 51 Ap, Am, and "normal" stars. It is found that stellar wavelengths do occasionally coincide with those of actinide spectra, and that occasionally these coincidences are improbable; that is, the probability that they would arise by chance is in the range 0.005 to 0.05. It is nevertheless concluded that most of these coincidences *have* arisen by chance, in this rather extensive search. We specifically discuss thorium and uranium, which we believe *are* present in the rare-earth maximum spectrum of HR 465.

Subject headings: line identifications — stars: abundances — stars: metallic-line — stars: peculiar A

The purpose of this paper is to report on a search for the actinides in the spectra of 51 peculiar, metallic-lined A, and normal A stars. Most of the spectra that we have examined were taken at the Dominion Astrophysical Observatory and have a dispersion of 2.4 Å mm^{-1} . This is perhaps the highest dispersion survey for the actinides that has been made of a large number of stars, and that employs up-to-date laboratory wavelength lists with allowance for isotope shifts (see below).

Adelman (1972, 1973a, b) searched for a number of actinides in his study of 21 cool Ap stars, although he concentrated on uranium and thorium, for which the laboratory wavelengths were most reliable. A number of individual stars have been examined by various workers (cf. Adelman and Shore 1973; Jaschek and Brandi 1972; Kodaira 1974; Pyper and Hartoog 1975; Galeotti 1974; and others reviewed by Kuchowicz 1973).

The method that we have used for element identification has been described by Hartoog, Cowley, and Cowley (1973, Paper I) and Cowley, Hartoog, and Cowley (1974, Paper II), and makes use of a statistical analysis of wavelength coincidences between the strongest lines of each ionic species and a stellar line list which is complete over a wavelength interval (approximately $\lambda\lambda 3750\text{--}4650$ in this study) to the limit of line detectability. This method is well suited for the detection of trace elements which have rich spectra, such as the lanthanides or actinides. Most of these elements have spectral line intensities that become gradually weaker, with no large discontinuity in intensity such as occurs, for example, in Ca II between the H and K lines and the next strongest lines. (Eu, Yb, and Am are exceptions.) Because of this, there is

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no easily recognizable, simple pattern of lines, and this is especially true when the strongest lines of the element are weak or only of moderate intensity in the star. Conventional identification techniques rely heavily on the recognition of characteristic patterns of lines, while the statistical method only requires a number of wavelength coincidences that is significantly above average. It can give very useful results even when a particular pattern of lines has been badly perturbed by blends. It is important to point out, however, that the statistical method has only been used as a supplement for the conventional techniques, which are also employed.

The stars for which the survey was carried out are listed in Table I. Many of these stars have too high rotational velocities for a realistic survey for the actinides, but they are included for completeness. The spectra given in parentheses after the star names are those for which an improbable (i.e. probability ≤ 0.05) number of coincidences of actinide lines with the stellar wavelengths occurred. As will be seen below, we regard most of these cases as improbable coincidences, but chance coincidences nevertheless. At the present time, we are unable to convince ourselves that there is compelling evidence for a transuranic actinide in any star that we have studied. For uranium, the statistical evidence is good only in the exceptionally peculiar star HR 465 (Cowley and Hartoog 1972), and even here the skeptic may find some basis for pessimism in the peculiar distribution of wavelength residuals discussed by Cowley and Adelman (1973).

Nevertheless, in spite of some misgivings, we feel that uranium is weakly present in a number of Ap stars (cf. Paper II and references therein), and it is against this backdrop that we wish to discuss the problem of the remaining actinides.

PECULIAR AND METALLIC-LINED A STARS

TABLE 1
LIST OF STARS SURVEYED

Normal (?) Stars	
28 And (Pu II) 23 Cas , Her η Oph	o Peg 15 Peg (Pu II, Cf) HR 8226 HR 9015
Am-Fm Stars	
32 Aqr (Th II) π ² Boo 17 Com B = HR 4751 ζ ¹ Lyr	ε Ser 63 Tau τ U Ma ζ U Ma B (Pu II)
Magnetic Ap	
10 Aql 49 Cnc (Cf II) β CrB 4 Cyg (Cm II) 73 Dra γ Equ 52 Her 45 Leo (Am II) κ Psc 78 Vir HR 465, RE max U II, Th II	HR 465, in 1974 HR 4816 HR 4854 HR 7058 (Np II, Cm II) HR 7575, in 1971 (Es II) HR 7575, in 1974 HD 25354* HD 25354† (Cm II, ²⁴⁷ Cm II) HD 51418 (Cf II) HD 200311
Manganese Stars	
α And (Cf II) π ¹ Boo κ Cnc ι CrB (Cm II) γ Crv (Am II) 46 Dra A 46 Dra B ν Her	φ Her μ Lep (Cf II) 53 Tau HR 205 (Pu II) HR 1800 (Pu II) HR 2844 HR 4072 HR 7664
Other	
3 Cen A	

* Plate Pb 11251 (see Pyper and Hartoog 1975).
† Plate Pb 11422 (see Pyper and Hartoog 1975).

Thorium is the only actinide other than uranium with an isotope having a half-life greater than a billion years. It is harder to identify than uranium because it has fewer strong lines. In HR 465, a moderate feature was measured 0.01 Å away from λ4019.13, which is the strongest line of Th II. Bidelman identified the line as Th II in his unpublished wavelength list for this star. Adelman (1973*b*) suggested that thorium might be present in HD 18078, 81009, and 165474. In HD 200311, Adelman (1974) measured a weak feature at λ4019.17, which he concluded could *not* be attributed to Th II because of the temperature of the star. Our own survey has failed to detect a line within 0.04 Å of λ4019.13 in any star except HR 465; we take this as evidence that a faint line of a common element is not responsible for the feature in HR 465, although a chance coincidence with some doubly ionized lanthanide line is always possible.

The statistics of the wavelength coincidences for Th II in HR 465 are summarized in Table 2. The

notation and procedure are the same as in Paper II. All of the results are based on 2,000 sets of nonsense wavelengths. Two thorium line lists were used, one containing the 39 lines of Th II with intensities greater than 500, and a shorter list of seven lines with intensities greater than 1,000. The wavelengths and intensities are from Meggers, Corliss, and Scribner (1975). The results indicate a significant number of wavelength coincidences. The case for the identification is strengthened somewhat by the fact that the significance improves at the smaller wavelength tolerances.

In summary, we believe that Th II is probably present in the rare-earth maximum spectrum of HR 465 (cf. Cowley, Allen, and Aikman 1975), and by extension, in other Ap stars as well, but the statistical evidence is not as convincing as in the case of uranium.

In view of the difficulty in finding uranium, and the even greater difficulty with thorium, is there any possibility that one could establish the presence of any other actinide? Certainly the only hope would be to

TABLE 2
SIGNIFICANCE TESTS FOR THORIUM IN HR 465

Tol	H/N	p
± 0.01.....	6/39	0.022
± 0.02.....	8/39	0.054
± 0.04.....	14/39	0.040
± 0.06.....	16/39	0.206
± 0.01.....	3/7	0.007
± 0.02.....	4/7	0.005
± 0.04.....	4/7	0.052
± 0.06.....	5/7	0.061

NOTES.—Tol, wavelength tolerance for a coincidence, in angstroms; H, number of coincidences; N, number of lines sought; p, an estimate of the probability that the H coincidences arise by chance.

find stars for which nucleosynthesis had occurred within a few half-lives of the isotopes of the elements in question. Some of the transuranic nuclides have substantial half-lives (cf. Table 3), so that we would not require that a supernova have been observed during recorded history if we were to observe, for example, neptunium in some bright Ap star.

There are two immediate problems with the attempt to establish the presence of any transuranic element. The first is that the published laboratory wavelengths are not all of high accuracy; many wavelengths are quoted only to the tenth of an angstrom, and in some instances it is uncertain whether the line arises from the first or second spectrum. We have made use of unpublished wavelength lists for Cm II, Pu II, and Np II that were generously made available by Drs. Earl Worden and Mark Fred. The accuracy of these wavelengths is in all cases better than 0.01 Å, which is more than sufficient for our purposes.

A second difficulty is that the laboratory wavelengths do not always correspond to the longest lived isotopes. This was not true for Np II, but for plutonium the measured isotopes were ²³⁹Pu and ²⁴⁰Pu, while for curium they were ²⁴²Cm, ²⁴⁴Cm, and ²⁴⁶Cm. Because of the large nuclear volumes, isotope shifts can be very large, amounting to tenths of angstroms in some cases. Unless these shifts are taken into account, it would be virtually impossible to identify spectra arising from one of the long-lived isotopes. For Pu and Cm, we have prepared approximate wavelength lists for the longest lived isotopes, by extrapolation of the measured isotope shifts. We are indebted to Drs. Worden and Fred for their advice and help in this matter.

Table 4 lists the spectra for which a search was carried out, along with a reference to the wavelengths that were used. The number of lines in each spectrum that are actually sought varies slightly, depending on the wavelength range of the measurements in a given star. The figures listed in Table 4 were taken from the results for HR 7575 and are representative.

In a survey of 14 laboratory spectra in the spectra of some 50 stars, it is inevitable that purely chance coincidences will occur at the 95 percent and higher confidence levels. In principle, one can calculate the

expected number of results at a given confidence level that are due merely to chance, but this is difficult to do quantitatively because the stellar spectra are correlated with one another; if an Fe II line coincides with a Cm II wavelength in one star, it is likely to do so in the next. If we ignore this difficulty, the results of our survey may be summarized as follows. Some 54 stellar spectra were searched for 14 spectra of the actinides. There were 20 "marginal" results (not counting U II and Th II in HR 465), with the probability of occurrence by chance between 0.05 and 0.005. We would expect (ignoring correlations) between 3.8 and 38 such results. We see no basis in these figures for belief that any actinide has been detected.

Statistical calculations of this nature do not apply to individual stars. Here, we have attempted a line-by-line examination of the wavelength coincidences (or lack thereof). For uranium and thorium, we simply searched our wavelength lists to see if the strongest line of each element was measured. The thorium line, Th II λ4019.13, has been discussed above, and we have little to add to the discussion of Cowley and Adelman (1975) of U II λ3859.61, except to note that the line is absent from the spectra of the manganese stars, and the sharp-lined Am stars 63 Tau and 32 Aqr. In τ UMa, we noted an asymmetry in the violet wing of Fe I λ3859.91. The line widths in τ UMa are sufficiently broad that λ3859.61 could not be expected to appear distinctly. As was noted by Cowley and Adelman, there is a good chance of an unresolved blending line that perturbs the stellar wavelength of λ3859.61, so that it is difficult to evaluate the asymmetry in λ3859.91 in τ UMa. The remaining Am stars that we have studied do not have sufficiently sharp lines for us to say anything about the possible uranium feature. Thus there are insufficient data for any kind of generalization regarding the occurrence of this feature in the Am stars.

Our negative result for uranium and other actinides in κ Psc is rather surprising in view of the large number of U II lines reported by Galeotti (1974) for this star. On the two plates we examined, we could find no convincing evidence for *any* U II lines, nor of the other heavy ions he suspected to be present. Line blending is a serious problem in this star, which has a rotational velocity $v \sin i$ of 34 km s⁻¹ (Preston 1975); also spectral variations are present to confuse the line identifications. It would be of interest to reexamine the line identifications using a number of plates well distributed in time of observation over the 0.658 period of variation.

TABLE 3
HALF-LIVES OF THE MORE STABLE ACTINIDES
IN YEARS

²³² Th.....	1 × 10 ¹⁰
²³⁵ U.....	7 × 10 ⁸
²³⁸ U.....	4 × 10 ⁹
²³⁷ Np.....	2 × 10 ⁶
²⁴² Pu.....	4 × 10 ⁵
²⁴⁴ Pu.....	8 × 10 ⁷
²⁴⁷ Cm.....	2 × 10 ⁷

TABLE 4
SPECTRA FOR WHICH SEARCH WAS CONDUCTED

Spectrum	Reference	No. of Lines (see text)
Ac II.....	Zaidel' <i>et al.</i> 1970	14
Th II.....	Zaidel' <i>et al.</i> 1970	23
Pa II.....	Zaidel' <i>et al.</i> 1970	11
U II.....	Zaidel' <i>et al.</i> 1970	30
Np II.....	Fred (1974)	5
²⁴⁰ Pu II.....	Fred (1974)	32
²⁴⁴ Pu II.....	Fred (1974)	32
Am II.....	Zaidel' <i>et al.</i>	14
²⁴⁴ Cm II.....	Zaidel' <i>et al.</i> (1970), Worden (1974)	52
²⁴⁷ Cm II.....	Worden (1974), Conway and McLaughlin (1956)	26
Bk II.....	Zaidel' <i>et al.</i> (1970)	3
Cf ?.....	Zaidel' <i>et al.</i> (1970)	10
Cf II.....	Worden and Conway (1970)	2
Es II.....	Zaidel' <i>et al.</i> (1970)*	3

* A more accurate line list is now available (Worden *et al.* 1974).

The results for curium in HD 25354 were briefly discussed by Pyper and Hartoog (1975). In examining this element, many different laboratory wavelength lists were prepared. This element was studied in some detail because one of the plates, Pb 11422, showed that an improbable number of wavelength coincidences occurred with one of the early wavelength lists for Cm that was used.

Unfortunately, as "better" wavelength lists were tried, the statistical results became worse. This is illustrated in Table 5, where the results are shown for three ²⁴⁷Cm wavelength lists. The first list (A) was

TABLE 5
SIGNIFICANCE TESTS FOR CURIUM-247 ON THE PLATE Pb 11422 OF HD 25354

Tol (Å)	H/N	p	R
A. ²⁴⁷ Cm I and ²⁴⁷ Cm II (Conway and McLaughlin 1956)			
± 0.04	12/66	0.11	100
± 0.06	20/66	0.007	1,000
± 0.08	23/66	0.01	100
± 0.10	27/66	0.01	100
B. ²⁴⁷ Cm II (Conway and McLaughlin 1956)			
± 0.04	7/34	0.11	100
± 0.06	11/34	0.03	500
± 0.08	11/34	0.12	100
± 0.10	14/34	0.09	100
C. Strongest ²⁴⁷ Cm lines (Worden, private communication)			
± 0.04	2/18	0.56	100
± 0.06	3/18	0.57	100
± 0.08	3/18	0.88	100
± 0.10	5/18	0.61	100

NOTES.—R, number of random wavelength sets upon which p is based; Tol, wavelength tolerance for a coincidence, in angstroms; H, number of coincidences; N, number of lines sought; p, an estimate of the probability that the H coincidences arise by chance.

prepared from the material of Conway and McLaughlin (1956), and contained both Cm I and Cm II wavelengths. At the temperature of HD 25354 one would not expect Cm I to be present, so an "improved" list (B) of only Cm II lines was prepared, using an unpublished list of Cm I and Cm II lines kindly supplied by Dr. Earl Worden. This list gives a somewhat lower statistical significance. Finally, a list (C) of the strongest lines of Cm II was prepared. It gives no statistical significance at all. An examination of the tracings shows that almost all the stellar lines which coincide with the strong Cm II lines can be attributed to other elements which *are* present in the spectrum. We thus conclude that Cm is probably *not* present in this spectrum.

In the case of the other actinides with a marginally significant number of wavelength coincidences, we made an attempt to assign the coincidences to other more likely elements. A detailed accounting of this kind of procedure for trace elements was given in Paper II, and will not be repeated here. The work is enormously time-consuming, as well as frustrating. Some marginal results can be immediately dismissed, but in many cases one finds a number of lines for which no plausible alternate is available. One is then left with questions concerning the relevance of laboratory intensities to stellar work, the completeness of the laboratory wavelength lists, and the accuracy and relevance of the laboratory wavelengths themselves, in the light of hyperfine structure, isotope shifts, and Zeeman broadening. There are no easy answers to these questions.

We summarize the results of our search for the actinides as follows: uranium is (almost) certainly present at rare-earth maximum in the spectrum of HR 465, and it is probably present in a number of other Ap stars (cf. Paper II as well as Cowley and Adelman 1975) and the 1974 spectrum of HR 465. Thorium is probably present in the rare-earth maximum spectrum of HR 465. For the remaining actinides, there is no doubt that there are a number of improbable coincidences with laboratory spectra of these elements,

especially Cm II, and this undoubtedly accounts for a number of published preliminary identifications of the actinides. Our assessment of these coincidences is that, although they are somewhat improbable (probability 0.005–0.05), one may nevertheless ascribe them to chance.

The problem of establishing a credible spectral identification for an actinide is immense. The required overabundances are very large (cf. HR 465), and the stellar spectrum is certain to have an enormous line density from all of the other elements with complex spectra that would also be present. Even a modest stellar rotation ($\geq 5 \text{ km s}^{-1}$) can blend these lines and perturb the wavelengths. To these factors we must add the intrinsic blurring of the spectra themselves due to

isotope shifts (when several isotopes are present, some with hyperfine structure) and the Zeeman effect.

Despite these difficulties, we feel it is important to extend the search for actinides to select faint Ap stars having rich spectra with ultrasharp lines, such as HD 221568 (Kodaira 1974) and those studied by Adelman (1973*b*) in which the Th II spectrum is suspected to be present.

We are indebted to Earl Worden and Mark Fred for providing us with their actinide line lists prior to publication. Thanks are also due to Diane Pyper for her stellar line list for HD 25354, to Saul Adelman for his stellar line list for HD 200311, and to W. P. Bidelman for the loan of his spectrograms of HR 465.

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