THE ASTROPHYSICAL JOURNAL, 321:553–559, 1987 October 1

IDENTIFICATION OF LINES IN THE SATELLITE ULTRAVIOLET: THE SPECTRUM OF TAU SCORPII

CHARLES R. COWLEY AND DONALD R. MERRITT
Department of Astronomy, University of Michigan
Received 1987 January 26; accepted 1987 March 23

ABSTRACT

The method of wavelength coincidence statistics (WCS) is applied to the ultraviolet spectra of τ Sco obtained by the *International Ultraviolet Explorer* (*IUE*). No identifications of elements heavier than Zn were made. With the exception of Zn IV, all identifications had been previously made in an exhaustive study of *Copernicus* spectra by Rogerson and Ewell. A comparison of the identifications made in the two studies is in very good agreement for those spectra rich in lines, where the WCS parameters indicate the strong presence of the species. Useful information is added by WCS in cases where species are only weakly, or arguably, present. We show that WCS is an important tool in the exploration of any complicated stellar spectrum, and even in the case of a spectrum that has been well studied by traditional methods, it adds important information.

Subject headings: line identifications — stars: individual (τ Sco) — ultraviolet: spectra

I. INTRODUCTION

Hartoog, Cowley, and Cowley (1973) first introduced the automated technique of wavelength coincidence statistics (WCS) in connection with the identifications of rare earths in the very complicated spectra of peculiar A stars. Some of these stars have extraordinarily high densities of lines, and an *objective* conclusion about the presence or absence of a trace species is desirable.

The satellite ultraviolet spectra of commonplace stars is perhaps even richer in lines than those of the Ap stars obtained with ground-based instrumentation. However, few astronomers have taken advantage of the methods of WCS which are now well documented (cf. Cowley and Hensberge 1981).

Hensberge and his colleagues (cf. Hensberge *et al.* 1986) and Bord and Davidson (see Bord and Davidson 1985) applied WCS to the analysis of ultraviolet spectra of CP stars, while Chjonacki, Cowley, and Bord (1984) showed how theoretical intensities could be used to investigate the intensity *threshold* for a species that was well identified; that is, the theoretical strengths at which the lines could be judged only as marginally present.

It has seemed worthwhile to apply the technique to the spectra of some more commonplace stars, especially, the slowly rotating B stars such as τ Sco or 10 Lac, to see if any exotic species would be revealed. We also wish to explore possible new insights to be gained from the application of WCS to a spectrum that has been well studied by traditional methods. The present study reports the results for the first of these two stars.

II. REMARKS ON THE PURPOSE OF A QUALITATIVE SURVEY OF A STELLAR SPECTRUM

There were two main historical reasons why qualitative analyses of stellar spectra were pursued. The first, and obvious reason, was simply to get an idea of the identifiable elements in the spectrum and to make a comparison with other stars. The second was to aid in the subsequent, quantitative analysis of a star.

Abundance analyses of late-type stars—the traditional objects upon which studies of the chemical evolution of the Galaxy were based—used lines whose identifications were made primarily with the help of the Rowland tables. Greenstein (1948), whose work was seminal for many abundance studies of the 1950s and 1960s, wrote that "For use, a line should be substantially unblended in the Sun, in α CMi, and in the supergiants." From a practical standpoint, "unblended" meant that the person who had done the line identification work made only one suggestion for the identification of a feature. It was then, and still is, common practice for those doing identification work to write several possibilities beside a measured stellar wavelength, and in such an instance, the feature would be considered to be "blended."

In the satellite ultraviolet, in the molecular-rich infrared, and in the complex spectra of Ap stars, it is well known that the presence of a single entry in a line identification study by no means ensures that the feature is unblended in the sense required for abundance work.

III. OBSERVATIONAL MATERIAL AND ITS REDUCTION

We examined the *IUE* archives for images of τ Sco with optimum photometric exposures. The present work is based on the following SWP images of τ Sco: 16223, 17480, 19230, and 22177. Data tapes were obtained from the National Space Science Data Center, and reduced with the help of the program VIRIS (Desko, Bord, and Davidson 1986). Our implementation of the program differs slightly from that described in the reference. We employed a "rotational" filter to all orders. More precisely, we convolved the log (IUE FLUX)'s with the function $P(\Delta\lambda)$ given, for example, by Cowley (1970, eq. 5–2.11). We chose $\beta = 1.5$, and $v \sin (i) = 2.0$.

Noisy data at the ends of the orders were trimmed, as in Desko *et al.* but the rectification was automated with the help of the IMSL cubic spline data smoother ICSSCV (IMSL 1982). The trimmed data points in each order were divided into 15 intervals, and the highest point within each interval was provisionally chosen as "a" pseudocontinuum point. An additional condition was imposed that no such point could be lower than a linear interpolation between the neighboring points. The effect of spuriously high data points was controlled only by the spline smoother, and it cannot be claimed that the net result is as satisfactory as would be obtained from a visual inspection and by-eye choice of each pseudocontinuum point. We felt that as an overall technique, the sacrifice in accuracy would be made up by the time saved.

Rectified intensities were obtained with the help of the continuum points, as in the procedure of Desko *et al.* The orders were then combined into a single data vector with a program (MERGE) written expressly for this purpose. The individual data points for each order were first linearly interpolated at each 0.02 Å. Overlapping intensity data were averaged.

The treatment of missing data was contingent on the next step. Since wavelength measurements were made on individual frames using LINPOS (see below), a flat continuum equal to 1.00 was interpolated, and the real data were modified with a cosine bell to merge smoothly to the assumed data. In the current implementation, the cosine bell was applied to 100 data points (2 Å) on either side of assumed data. This particular procedure was used to avoid the introduction of harmonics in subsequent Fourier smoothing prior to wavelength measurement by LINPOS.

The data vectors were measured for wavelengths using the program LINPOS (Rice 1981). Our decision to employ LINPOS rather than the subroutine SLOPES of the package VIRIS of Desko *et al.* was based entirely on our familiarity with the former program and not on any tests of the relative effectiveness of the programs.

We shall not discuss in detail the adjustable parameters of LINPOS, which are described in the reference cited. A number of refinements have been made since 1981, but they are largely cosmetic. Experience has shown (C. R. Cowley, unpublished) that plates measured with the Grant-type engine (ARCTURUS) of the Dominion Astrophysical Observatory (DAO) yielded consistently higher WCS parameters for well-identified species than the same plates measured with LINPOS. However, the sacrifice in accuracy has been considered to be more than offset by the saving in time that resulted from the use of the automated measuring procedure.

After LINPOS became available, I (C. R. C.) stopped using ARCTURUS entirely.

A radial velocity was obtained for each *IUE* frame using the technique of Bord and Davidson (1985). The lines used to determine the shifts were strong lines of Fe III, IV, and Ni IV. Table 1 shows the values found for the four images.

The number of lines measured is strongly influenced by the "depth parameter" of LINPOS which determines a minimum depth that a feature must have in order to be measured. For the *IUE* data, we used a depth minimum of 0.1. For comparison, we have found 0.02 to be a satisfactory minimum depth for DAO plates that have been digitized with a PDS.

Another important factor is the severity (cutoff) of the Fourier filter. A default "filter" is chosen by LINPOS as described by Rice. While this default has usually been satisfactory for photographic plates, we have found it necessary to override the default to produce considerably more severe filtering, typically retaining half of the harmonics that would be retained by the default filter.

The four *IUE* frames were added with the help of the DAO program COMBINE (see Hill and Fisher 1986). We used the original files, created with the program MERGE. This does not properly treat regions for which data were available from one of the frames but not another. In the present instance, all four frames are of the same spectral region, and the resulting data degradation was minimal.

TABLE 1

RADIAL VELOCITIES OF *IUE* IMAGES OF τ SCORPII

Frame	Number of Lines Measured	Radial Velocity
16223.........	2868	−2.5
17480.........	1535	7.6
19230.........	2861	1.1
22177.........	2889	−2.0

IV. THE IDENTIFICATION OF ATOMIC SPECTRA

A variety of WCS tests were made on two sets of wavelength measurements using LINPOS on the co-added *IUE* spectra. Measurements of 2251 lines were made with the depth criterion set to 0.1, while 1445 lines were measured with this parameter set at 0.2. WCS tests were made with three main data sets, based on Kelly (1984), Reader and Corliss (1980), and Kurucz and Peytremann (1975, henceforth, KP). In each case, we included the first through fifth spectra (from neutral to 4 times ionized atoms). Generally, the number of lines in the Reader and Corliss tables are significantly shorter than in the other two data sources. Depending upon the nature of the atomic spectrum and its representation in the star, more significant WCS parameters may arise from a short list of strong lines. It is therefore important to run tests with both kinds of lists, and this has been done.

Rogerson and Ewell (1985, henceforth RE) have discussed extensive line identification work based on *Copernicus* spectra of τ Sco in the region $\lambda\lambda$949–1560 (see Rogerson and Upson 1977). Their work is summarized in a table of "Identified Ions" containing 49 ions from 25 elements. Their table includes all the spectra which we may consider "well identified" in the *IUE* data by WCS. Thus, the answer to our question (§ I) whether WCS might reveal the presence of additional, exotic species in τ Sco is for the present, with the minor exception of Zn IV, "no."

A less spectacular, but perhaps ultimately more useful, question is whether WCS has anything positive to add to a study that has been as carefully carried out as that of RE. These authors predicted the positions and strengths of features based primarily on the extensive data tabulations of Kelly (1981) and KP and Kurucz (1981). They give additional references and document their technique for estimating strengths when *gf*-values were unavailable.

In Table 2, we make a comparison of identifications by RE and WCS for the 14 spectra for which RE list 20 or more identified lines. The WCS entries are for the laboratory wavelengths of Kelly, and the list of 2251 wavelengths. RE made identifications of 28 spectra on the basis of fewer than 10 lines. In these instances, WCS is at the obvious disadvantage of dealing with statistics of small numbers. Such cases are therefore less relevant to the present discussion which is concerned with instances in which WCS has useful advantages.

The first two columns of the table give the spectra and the number of lines identified by RE. The next three columns are parameters from WCS. Cowley and Hensberge (1981) and references mentioned therein give a detailed explanation of the meaning of these parameters. Briefly, H/N is the number of coincidences, or "hits" H out of N laboratory lines sought. The tolerance for a hit is ± 0.06 for the parameters in Table 2. The parameter "p" is a Monte Carlo estimate of the probability that the H coincidence arise by chance. Since this estimate is

TABLE 2

IDENTIFICATIONS BY WCS AND RE

			WCS			
SPECIES (1)	N(RE) (2)	H/N (3)	S (4)	p (5)	*Copernicus* (6)	OK? (7)
C II	40	12/24	3.7	0.005		A
C III	49	32/49	5.4	<0.005		A
Ca III	23	44/150	0.8	0.24	A	R
Cr III	276	322/1198	−0.9	0.86	A	R
Cr IV	257	75/150	5.1	<0.005		A
Fe III	626	308/617	16.2	<0.005		A
Fe IV	159	414/595	20.1	<0.005		A
Fe V	150	190/441	4.1	<0.005		A
Mn III	304	182/849	−1.6	0.94	?	R
N I	23	55/142	−0.2	0.58	A	R
N II	48	20/80	−0.5	0.69	A	R
N III	29	45/113	3.5	<0.005		A
Ne II	29	46/187	−0.25	0.61	?	R
Ni III	54	159/396	9.0	<0.005		A
Ni IV	54	264/438	11.8	<0.005		A
O III	40	21/40	4.3	<0.005		A
P III	91	39/126	−0.36	0.64	?	R
P IV	72	51/119	2.1	0.02	A	A
S II	46	5/16	0.7	0.31	?	R
S III	27	11/16	2.5	0.02	A	A
Si III	119	75/110	7.5	<0.005		A
Si IV	27	9/17	1.5	0.12	A	R
Zn III	32	8/36	1.1	0.18	?	R
Zn IV	0	66/222	2.6	0.005	?	R

based on 200 trials, the smallest values are listed as less than 0.005. Roughly speaking, S is a measure of the significance of the H hits in standard deviations (σs).

We have also analyzed REs own wavelength measurements, by WCS with the help of a data tape kindly made available to use by J. B. Rogerson. In addition, we have obtained a digitized version of REs τ Sco atlas from the National Space Science Data Center. This digitized version has been extremely useful in conjunction with our auxiliary programs. For example, we have remeasured the spectrum with LINPOS and made a complete WCS analysis based on our own measurements as well as those of RE. We have also made extensive use of our program PLTFTS to display and measure the wavelengths of specific features.

We briefly summarize the results of the examination of the *Copernicus* material in column (6) of Table 2. An "A" in this column means that the WCS analysis of the *Copernicus* data agrees with that of the *IUE* measurements. If a "?" occurs, remarks are found in the text below.

In the last column of Table 2, we enter an "A" if we feel the overall agreement between WCS (of either the *IUE* or *Copernicus* material) and RE is satisfactory. When an "R" is listed, the spectrum is discussed below.

We should say at the outset, however, that the failure of WCS to find a *significant* number of coincidences can by no means be accepted as a *proof* of the absence of a species. The converse, however, is true: a significant fraction of coincidences precludes chance occurrences of the coincidences (at some specified confidence level). For this reason, when an "A" appears in the last column, no further discussion is required.

V. INTENSITY PARAMETERS

In connection with the discussion of individual spectra, we shall make use of theoretical intensity estimates for the strengths of various atomic lines. We have followed a procedure very similar to that of RE, using the oscillator strengths calculated by KP, combined with the solar abundances (Anders and Ebihara 1982) which were assumed to apply to τ Sco. We used a temperature of $5040/0.16 = 31{,}500$ K, and a log (P_e) of 3.0. Ionization and excitation were computed in LTE. Partition functions for the first through fifth spectra were based on atomic energy tables (Moore 1949, 1952). For the first through fourth spectra of chromium and manganese, which were important in the present discussion, we made new calculations using Sugar and Corliss (1986). The *intensity parameter* (IP) for a given line, to which we shall refer below, is the *logarithm* of the number of absorbers of the line in question multiplied by the *gf*-value taken from KP. The total number of atoms was normalized in the usual way to 10^{12} for hydrogen.

The KP line list is very incomplete, and this is especially true for the third and fourth spectra of the iron-peak elements. The current revision of this indispensable work (Kurucz 1986) will ease many of the problems encountered in this study, but the incompleteness of atomic data is still a problem of concern throughout much of spectroscopic astrophysics (cf. Johansson and Cowley 1986).

RE's "fictitious strength, S" should equal our IP apart from an additive constant, and differences resulting from slightly different values of T_e and log (P_e). However, there are many more lines of Cr III and Mn III, for example, in Kelly's (1984) compilation than in KP. RE took an oscillator strength of unity as "an upper limit" for most of these lines. This may be responsible for the assignment of Mn III (and some other ions) to numerous features in cases where we feel it may have been more useful to leave them unassigned (see below).

A further word about the use of predicted intensities in the identification of spectral features is warranted. In the case of well-identified species, it is straightforward to establish values of IP or "S" corresponding to lines whose strengths are (within a factor of 2 or so) at the threshold of measurement. In the case of well-identified species, it seems reasonable and proper to suggest that measured wavelengths of weak features that fall within some set tolerance may be attributed to the species in question.

RE, however, apparently used their S parameters also in the identification of weak features from atomic spectra, even in cases where the strongest predicted lines seem none too securely identified. This seems to be the case with Mn III, S II (apart from the interstellar lines, which are clearly present), and for a few other spectra. We do not say that they have erred in the case of any individual atomic spectra, but the procedure is philosophically unsatisfactory.

The S parameters are based on an assumed (solar) abundance. It is improper to rely on this *assumption* in order to make identifications *when the strongest expected features* are themselves weakly represented in the star. Our own experience is that judgments in such cases are too prone to subjective influence. One should therefore not bias his or her judgment with the assumption that he or she already knows the abundance, which may represent the ultimate goal of a survey of this nature.

In certain instances, one may infer the likely presence of a given atomic spectrum, say Mn III, from the definite, or probable, presence of the spectrum of an ion with one more or less electron, for example, Mn IV (but see comments below on Mn IV). Certainly, the inference is stronger than it would be if it were supported *only* by the *assumption* of a solar abundance and a subjective judgment concerning the presence of weak features. But the identification still rests on a variety of assumptions, such as LTE and the relative f-value scale between the relevant ions. It is more satisfactory to base judgments directly on a comparison between the atomic and stellar spectrum. WCS provides an *additional* basis for such a judgment in these cases (cf. the discussion of Cr III below).

VI. DISCUSSION OF INDIVIDUAL SPECTRA

1. Ca III.—This ion has the argon structure, and there are no dominating resonance lines. However, one of our surveys, that based on the Reader–Corliss line lists, yields highly significant WCS parameters with the shorter stellar line list (based on depths >0.2), when a tolerance ± 0.03 was used. We find $H/N = 11/54$. On the 200 nonsense wavelengths, the average H was 4.11 ± 1.68, giving an S parameter of 4.10; $p < 0.005$. There is no reason to doubt the presence of Ca III.

2. Cr III.—The WCS parameters in Table 2 reveal little or no evidence for the presence of Cr III. Since RE attribute nearly 300 lines to this spectrum, we have been at some pains to understand the situation. It may reasonably be argued that our 1198 laboratory lines from Kelly's list is simply too long. However, the shorter NBS lists give no better results with our *IUE* material.

On the other hand, RE's own wavelength list did give positive results for the NBS list, and the Kelly list just failed to qualify as a marginally significant result—the parameter P was 0.095. The NBS list yielded the following WCS parameters for a tolerance of ± 0.03 Å: $H/N = 34/52$, $S = 4.43$, $p < 0.005$. The spectrum of Cr III is surely present in τ Sco.

A reasonable explanation of the failure of the analysis of the *IUE* data to reveal the presence of Cr III is that it is of distinctly lower quality than the *Copernicus* material. Rogerson and Upson give a relation for calculating the "uncertainty of any point in the atlas"—essentially, the noise level. Values resulting from this formula are typically less than or equal to 1% for points near the continuum. This is well below the noise level that we estimate from our averaged *IUE* spectra, which may be over 10%, even for our averaged frames (see Fig. 1). Leckrone and Adelman (1986) give a general discussion of the noise in *IUE* spectra.

The question remains whether the intrinsically fainter lines among the 276 features attributed by RE to Cr III are appropriately designated. In raising this question, we grant that an identification study of this kind will inevitably result in misidentifications, especially among the fainter features. Nevertheless, it is well to know if the *fainter* 150 of REs Cr III lines are truly represented in the *Copernicus* material, and *whether the technique of WCS can add any useful information that will aid in the decision.*

We can answer this question in two ways. First, we can examine the equivalent widths of the intrinsically strongest Cr III lines in τ Sco. Here, we are forced to use the Rogerson-Upson atlas, since these features are essentially lost in the noise of our *IUE* material. Two lines that we believe to be representative are (stellar) $\lambda\lambda$1017.560 and 1033.442, which have IPs of 0.39 and 0.33. The equivalent widths of these features are difficult to measure precisely, but it seems safe to estimate that they are both in the range of 15 to 40 mÅ, and therefore *essentially on the linear part of the curve of growth.* Lines whose IP's average -0.6 should be roughly 2 to 4 mÅ in strength, and we conclude accordingly that lines with IPs less than or equal to -0.6 should be at or below the noise level.

A second approach to the question of identification of Cr III lines involves the use of WCS. For example, we have run tests with three specially chosen sets of 100 Cr III lines. They are described in Table 3.

We conclude that among the first set of lines of Table 3 a significant number are *sufficiently* strong to dominate the features in which they occur. This is at best marginally so for the second set and is no longer true for the third. We must keep in mind that the errors in the KP log (gf)s are surely of the order of a factor of 2 (or more) so that a *significant* portion of the lines in the first set may in fact have IPs near 0.5.

Of those lines identified by RE as Cr III for which there is a KP Cr III line within 0.02 Å of the relevant *laboratory* position, an overwhelming majority appear to be appropriately labeled—most of the IPs are greater than -1.

However, for more than half the features identified by RE as Cr III there is no KP wavelength within 0.02 Å, and therefore, no estimate of the intensity parameter. RE made use of expected line strengths within multiplets, but it is difficult to estimate the extent to which these efforts could realistically be applied to the large fraction of Cr III lines without KP oscillator strengths. But with WCS we can test for coincidence significance using the strongest set of Kelly Cr III lines that are *not* within 0.02 of KP wavelengths. The results of this test are shown in the last row of Table 3, and the coincidences, while not highly significant, are positive.

TABLE 3

TESTS AT ± 0.03 Å WITH Cr III LINES

IP Range	Mean IP	H/N	$\langle H \rangle$	σ_H	p
-1.4 to 0.5.........	-0.6	59/100	38.2	5.0	<0.005
-2.9 to -1.4.........	-2.1	45/100	38.1	4.5	0.07
-6.1 to -3.0.........	-3.9	39/100	38.1	4.8	0.45
Non–Kurucz-Peytremann.........		48/100	38.0	5.0	0.02

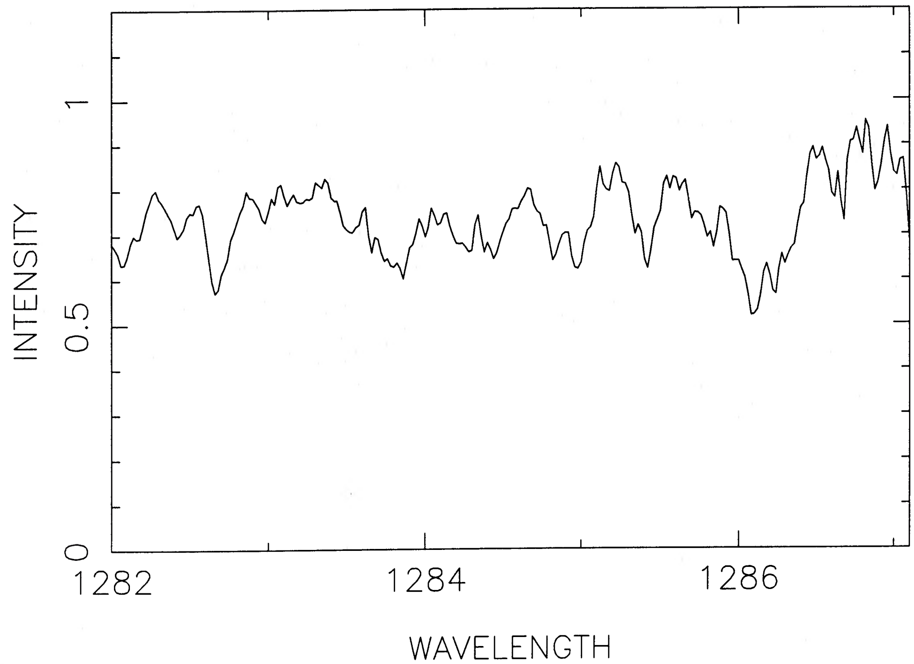

Fig. 1*a*

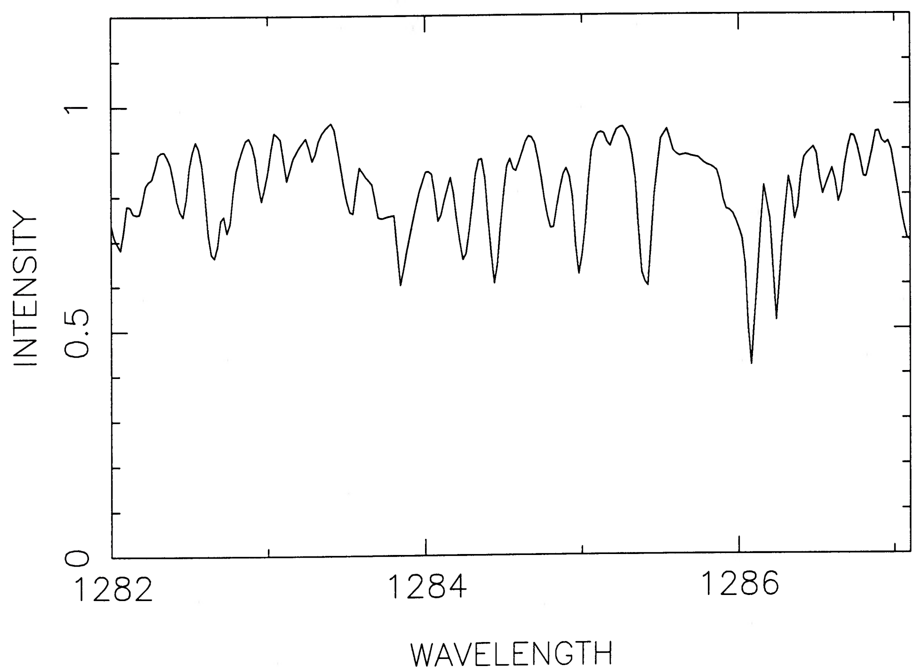

Fig. 1*b*

Fig. 1(*a*).—*IUE* averaged spectrum λλ1282–1287. (*b*) *Copernicus* spectrum λλ1282–1287. Both the resolution and noise level seems superior to the *IUE* material. A slight degradation of the Rogerson-Upson data may be noticed. It results from interpolations between their points necessary to make their digitized spectra compatible with our software.

We conclude that the vast majority of the features designated by RE as due (at least in part) to Cr III are correct. These are generally rather weak features, but the low noise level of the *Copernicus* material allowed meaningful identifications to be made of features that were well below the threshold of our *IUE* data.

3. Mn III.—The analysis of the *IUE* material is arguably less encouraging about the presence of Mn III than it was for Cr III. But in view of RE's identification of some 304 Mn III lines, we might expect a similar situation to that discussed for Cr III—the lower noise *Copernicus* material would support the identification. However, this does not appear to be the case.

We have performed a number of WCS tests with the RE wavelength list for τ Sco, and only one rather carefully chosen set of lines supports the identification. The situation is summarized in Table 4.

TABLE 4

TESTS WITH STRONG Mn III LINES

IP Range	$\Delta\lambda$	Mean IP	H/N	$\langle H \rangle$	σ_H	p
−0.7 to +0.1......	±0.03	−0.3	17/30	11.1	2.7	0.04
−0.7 to +0.1......	±0.06	−0.3	28/30	21.3	2.7	0.005
−0.8 to +0.1......	±0.06	−0.3	38/50	35.5	3.1	0.28
−1.2 to +0.1......	±0.03	−0.7	42/100	37.7	4.6	0.18

It appears that there is marginal support by WCS for the presence of a few of the strongest Mn III lines. The case is, however, far weaker than with Cr III, and it is certainly reasonable to ask why. The IPs give no clue, and it is desirable to have a careful abundance study of manganese in τ Sco to see if it is subnormal.

We have looked at a number of the intrinsically strong lines of Mn III on the *Copernicus* atlas. Weak (0.2–0.3 deep) features are present, at wavelengths that are arguably the right ones. According to WCS, we expect to find a measured feature within ±0.03 Å of *any* wavelength with probability 0.39; if the tolerance is ±0.06, the corresponding probability soars to 0.72. In this situation, the traditional identification techniques become *very* subjective.

We see little justification for designating some 300 wavelengths as due primarily or in part to Mn III. One could argue that the abundance is solar, and the Mn III features *must* make *at least* a minor contribution (say 5% or so). We feel an argument based on a WCS analysis of the stellar spectrum itself (as in the case of the Kelly Cr III lines) would be preferable.

4. N I.—Ultraviolet multiplets 1, 2, and 3 are represented by strong, deep features displaced by some 0.07 Å from the laboratory positions. RE enter an "*i*" for these nine lines. We have examined these features on the digitized version of the τ Sco atlas and remeasured the position of the features. Our results are in excellent agreement with those of RE; there is no doubt that the zero-volt N I lines are present in τ Sco. Moore (1975) lists a number of new zero-volt multiplets for N I, which contain additional lines designated as interstellar by RE.

WCS give marginally significant results—95% to 99.5% confidence—for *Copernicus* wavelengths, for both the RE and LINPOS measurements. The failure of the *IUE* WCS to give significance for N I is at least in part because strongest N I lines (according to our IPs) are shortward of the *IUE* data.

5. N II.—Ultraviolet multiplet 1 is clearly present. The lines are very strong. These particular low-excitation lines are not included in our *IUE* material. Of the 3058 wavelengths from the second-order *Copernicus* spectrum, RE attribute 46 features wholly or partially to N II. Of these, six are designated with "*i*" for interstellar.

It is not at all clear that any of the *other* features should be designated N II. If we purge the six interstellar lines from RE's list, and perform WCS tests for the remaining 40 wavelengths, we obtain no significance with a wavelength tolerance of 0.03 Å ($P = 0.71$!). With a tolerance of 0.06 Å, the p parameter is 0.06, but the test is already biased against the null hypothesis because we have used lines *already chosen by RE as N II*. None of our tests with the Kelly or Reader-Corliss lists (±0.03 and ±0.06) gave significance for N II, and these lists *included the interstellar wavelengths!* The failure for a positive result here is readily explained in terms of the high density in RE's line list and the small number of interstellar lines. We did obtain a positive result using 2273 LINPOS wavelengths (RE measured 3058). With a tolerance of ±0.06, the relevant figures are $H/N = 28/35$, $\langle H \rangle = 19.2 \pm 2.8$(s.d.), $p \leq 0.005$. If we subtract the six interstellar wavelengths, the results are again marginal.

Most of the questionable N II lines are not in KP, so we do not have IPs for them. The lines are mainly in multiplets with decimal designations, between 13 and 14 (Moore 1975).

It is not possible to reject the N II identification on the basis of traditional line-by-line inspections. The features designated N II by RE are certainly present, sometimes weak, sometimes blended, and sometimes rather far away in wavelength.

6. Ne II.—RE assign 25 second-order features wholly or in part to Ne II (the entry 29 in Table 2 includes first-order measurements). Of these lines, 15 are designated with an "*a*," meaning that they may be blended.

One of the six WCS tests with *Copernicus* data yields a significant number of coincidences: the Kelly laboratory list against RE's 3058 stellar positions. The tolerance ±0.06 gives $p = 0.01$, $H/N = 29/32$, $\langle H \rangle = 24.3 \pm 2.3$. The IPs for the strongest 20 lines in the range of the *Copernicus* data range from −1.6 to −0.4. The case for the identification of Ne II is not strong.

7. P III.—RE assign 91 wavelengths (at least partially) to P III, but WCS fails to allow rejection of the null hypothesis that coincidences are due to chance—both with the *IUE* and *Copernicus* wavelengths. An examination of the lines in ultraviolet multiplets 1 and 2 shows modest features (line depths some 0.2 to 0.3 of the local continuum), which might be attributed to P III. Without support from WCS, we are reluctant to accept the presence of so many features of this ion. A much more careful study is necessary for clarification.

8. P IV.—Even though there is an "A" in the last two columns of Table 2, we discuss this case briefly, since it was only a marginal (98% confidence) result. WCS tests of the *Copernicus* data support the presence of this ion. In addition, an examination of the *Copernicus* spectrum in the region of ultraviolet multiplet 2 shows, rather strong features (depths ≥0.5 with respect to the local continuum) at the expected wavelengths. The "marginally significant" results of the *IUE* material may therefore be accepted as a realistic indication of the presence of the ion.

9. S II.—None of our WCS tests gives support for the presence of S II. However, examination of the *Copernicus* spectra show that the zero-volt ultraviolet multiplet, No. 1, is almost certainly represented by three strong, deep features. RE designate them as (at least partially) interstellar. The identification of the remaining features (some 43 lines) may be questioned. The lines in ultraviolet multiplets 3 and 4 are 0.2–0.3 deep. Of the four lines, the $\Delta\lambda$'s are respectively 0.00, 0.05, 0.00, and 0.05. The presence of the weaker S II lines is questionable.

10. Si IV.—The Si IV spectrum is like that of sodium. The resonance lines at $\lambda\lambda$1393.76 and 1402.77 are enormous features in τ Sco, and the subordinate lines $\lambda\lambda$1122 and 1128 have marked wings. Of the remaining ($27 - 5 = 22$) Si IV wavelengths, the argument used by RE on the basis of their "*S*" parameters is sound, because the presence of the ion is ineluctably established by the resonance lines.

11. Zn III.—The ground term $3d^{10}\ ^1S$ is based on a completed subshell, and the resonance lines are at $\lambda\lambda$677.63 and 677.96—unfortunately, shortward of the stellar data. The lines that we can examine are considerably weaker (according to the Reader-Corliss tables). We have looked at eight lines in the *Copernicus* data. We cannot confirm the presence of Zn III. The situation is very similar to that for the noninterstellar N II lines, the Ne II lines, etc.

12. Zn IV.—This spectrum was not identified by RE, but

TABLE 5

WCS Tests for Zn IV

Stellar Data	Lab	$\Delta\lambda$	H/N	$\langle H \rangle$	σ_H	p
IUE (1445 lines)	K	± 0.06	94/222	75.4	7.5	0.01
IUE (1445 lines)	N	± 0.03	14/68	8.2	2.8	0.05
IUE (2251 lines)	N	± 0.03	16/68	12.8	3.3	0.37
Cop (RE lines)	N	± 0.03	35/59	23.6	3.5	0.005
Cop (LINPOS)	K	± 0.03	81/171	50.2	6.1	<0.005

WCS of both *IUE* and *Copernicus* data indicate its likely presence. The tests, with one exception, are consistently positive. We summarize their results in Table 5. Runs based on the Kelly line list are designated "K." An "*N*" indicates the Reader-Corliss (NBS) list.

The last entry leaves little doubt that Zn IV is present, since the number of lines upon which it is based means that Gaussian statistics should be rather well approximated, in which case, the $S = (81 - 50.2)/6.1 \approx 5$ is rather impressive.

We have looked at some dozen wavelengths in the *Copernicus* spectrum. The strongest lines in the Reader-Corliss list are $\lambda\lambda$1265.74 and 1306.66. RE measure features about 0.3 deep (a local line depth in units of REs "continuum") at $\lambda\lambda$*1265.72 and 1306.65, which they identify as O III λ1265.76 and Na II λ1306.62. We feel the examination of the individual features is consistent with the identification of Zn IV, but as in the cases discussed above, the judgment is *extremely* subjective.

VII. DISCUSSION

There are 11 spectra for which the WCS analysis of *IUE* material did not confirm identifications made by RE from the *Copernicus* observations: Ca III, Cr III, Mn III, N I, N II, Ne II, P III, S II, Si IV, Zn III, and Zn IV.

Of these cases, our own examination by WCS as well as traditional methods of the *Copernicus* spectra confirms the presence of roughly half of these spectra, viz.: Ca III, Cr III, N I, Si IV, as well as interstellar lines of N II, S II.

On the other hand, we feel that legitimate *questions* can be raised concerning the "identification" by RE of literally hundreds of features of Mn III, N II, Ne II, P III, S II, and Zn III. We do *not say* the modest claim by RE that at least a small contribution is due to these spectra is categorically wrong or highly suspect. But we claim it is unclear, that these (sometimes partial) "identifications" serve a useful purpose, and that our overall assessment is helped by access to WCS parameters.

The distinction is important for the question of whether our present knowledge of atomic structure is sufficient for the realistic analyses of ultraviolet stellar spectra such as that of τ Sco. The reader unfamiliar with the uncertainties of this kind of spectral analysis might consider the large percentage of "identifications" given by RE as an indication that missing atomic data was not a serious problem. We do not think such an attitude is warranted.

RE (*Copernicus*) and WCS (*IUE*) are in excellent agreement for 10 of the entries in Table 2; the number of cases becomes 11 if we include Zn IV. This is reasonable, since J. B. Rogerson has informed us privately that the Zn IV lines were inadvertently deleted from his data base. In our opinion, RE's methods would surely have identified this ion if they had looked for it.

We conclude that in a preliminary survey, especially one based on rather noisy material, WCS is of great value.

Even *after* the very careful study by RE of the high-quality *Copernicus* data, the WCS analyses have raised interesting points. For example: is the manganese abundance in τ Sco normal? RE *assumed* that it was, and on this basis identified Mn III. However, the assumption that all the abundances in an early-type star will be " solar," simply because a relatively small number have turned out to be *approximately* solar, deserves careful reflection. The analyses by WCS of the Cr III and Mn III spectra bring this point into sharp relief.

The method of wavelength coincidence statistics is ideal for the survey of material such as that obtained from *IUE*, where the noise level is relatively high. Anyone with modest computing facilities may readily implement the methods. New variations of WCS make increasing use of intensity information, and additional techniques in this direction are currently under development.

Any modern spectral survey that omits wavelength coincidence statistics can be regarded only as deficient.

We wish to thank J. B. Rogerson for a tape version of his Tables 3 and 4, and also for his comments on this manuscript. We thank Wayne Warren of the National Data Center for the digitized version of the *Copernicus* spectra. D. J. Bord and R. Desko provided invaluable help with the VIRIS software; J. B. Rice has updated his LINPOS code and discussed small but important modifications with us. G. Hill and Wesley Fisher have helped us in the use of their software. We gratefully acknowledge the assistance of W. C. Martin, J. Sugar, and A. Musgrove of the US National Bureau of Standards. We thank Paul Cobb for help with the data reduction. This research was supported by NASA *IUE* grant NAGS-251a.

REFERENCES

Anders, E., and Ebihara, M. 1982, *Geochim. Cosmochim. Acta*, **46**, 2363.
Bord, D. J., and Davidson, J. P. 1985, *Astr. Ap.*, **143**, 461.
Chjonacki, G. T., Cowley, C. R., and Bord, D. J. 1984, *Ap. J.*, **286**, 736.
Cowley, C. R. 1970, *The Theory of Stellar Spectra* (New York: Gordon & Breach).
Cowley, C. R., and Hensberge, H. 1981, *Ap. J.*, **244**, 252.
Desko, R. D., Bord, D. J., and Davidson, J. P. 1986, *Pub. A.S.P.*, **98**, 948.
Greenstein, J. L. 1948, *Ap. J.*, **107**, 151.
Hartoog, M. R., Cowley, C. R., and Cowley, A. P. 1973, *Ap. J.*, **182**, 847.
Hensberge, H., Van Santvoort, J., van der Hucht, K. A., and Morgan, T. H. 1986, *Astr. Ap.*, **158**, 113.
Hill, G., and Fisher, W. A. 1986, *Pub. Dom. Ap. Obs.*, **16**, 159.
IMSL 1982, *Library Reference Manual, ed.* 9, IMSL, Inc.
Johansson, S., and Cowley, C. R. 1986, in *Upper Main-Sequence Stars with Anomalous Abundances, IAU Colloquium 90*, ed. C. R. Cowley, M. M. Dworetsky, and C. Meigessier (Dordrecht: Reidel), p. 99.
Kelly, R. L. 1981, private communication to Rogerson and Ewell; the same, or an earlier version of Kelly 1984 (below).
———. 1984, private communication (23 megabyte data file).
Kurucz, R. L. 1981, *Smithsonian Ap. Obs. Spec. Rept.*, **390**.
Kurucz, R. L. 1986, Paper presented at the Colloquium on Atomic Spectra and Oscillator Strengths for Ap. and Fusion Research, Toledo, OH, 1986 August.
Kurucz, R. L., and Peytremann, E. 1975, *Smithsonian Ap. Obs. Spec. Rept.*, **362** (KP).
Leckrone, D. S., and Adelman, S. J. 1986, in *New Insights in Astrophysics: 8 Years of UV Spectroscopy*, (ESA SP-263), p. 65.
Moore, C. H. 1949, *NBS Circ.*, **467**, Vol. **I**.
———. 1952, *NBS Circ.*, **467**, Vol. **II**.
———. 1975, *Selected Tables of Atomic Spectra* (*NSRDS-NBS* **3**, Section **5**).
Reader, J., and Corliss, C. H. 1980, *Wavelengths and Transition Probabilities for Atoms and Atomic Ions* (*NSRDS-NBS*, **68**).
Rice, J. B. 1981, *Pub. Dom. Ap. Obs.*, **16**, 1.
Rogerson, J. B., Jr., and Ewell, M. W., Jr. 1985, *Ap. J. Suppl.*, **58**, 265 (RE).
Rogerson, J. B., Jr., and Upson, W. L. II. 1977, *Ap. J. Suppl.*, **35**, 37.
Sugar, J., and Corliss, J. 1985, *Atomic Energy Levels of the Iron Period Elements: Potassium through Nickel* (*J. Phys. Chem. Ref. Data*, **14**, Suppl. 2).

Charles R. Cowley and Donald R. Merritt: Department of Astronomy, University of Michigan, Ann Arbor, MI 48109–1090