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Abundance Patterns in Chemically Peculiar Stars of the Upper Main Sequence

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Abstract

Abundance patterns in chemically peculiar (CP) stars are discussed within the context of nuclear and non-nuclear mechanisms for the origin of the anomalies. Some abundance patterns depart significantly from " solar " but nevertheless show the signature of nuclear systematics. Other abundances are most difficult to reconcile with reasonable nuclear processes.

The empirical facts are presently far from being clear. Enormous selection effects influencing abundance systematics of CP stars have not yet been taken into account. Useful abundances are available for elements in the iron group and lighter, but for yttrium and the rare earths, uncertainties, including possible deviations from ionization equilibrium, are very large.

An approach via Chamberlain's Multiple Working Hypothesis is advocated. There is not yet a sound basis for rejecting either nuclear or non-nuclear mechanisms.

INTRODUCTION

Chemically peculiar (CP) stars of the upper main sequence have been discussed extensively in the literature. They were at one time among the most actively investigated objects in the domain of stellar astronomy, and interest in them continues at a high level. The stars offer observers a great variety of phenomena for investigation : they are light and spectrum variables, with unusual rotational and duplicity properties. Some pulsate, some are magnetic, and their spectra may well be the richest source of observational data on trans iron peak elements outside the solar system.

Some of the more important references on CP stars have been collecteed in Table 1. We have made no attempt at completeness. Secondary sources have generally been preferred, although a few papers have also been listed.

We mention briefly certain important results which will not be discussed further in the present article :

A large number of CP stars have been investigated by photometric methods which measure one or all of the diffuse absorption features found by Kodaira (1969). These features are especially important in statistical investigations of CP stars since they are less sensitive to rotational convolution than individual spectral lines. Similarly, the hydrogen line magnetometry of Landstreet and Borra offers the opportunity of eliminating the most obvious systematic effects with v sin i that so perturb coude spectra. It would be extremely valuable to have these measurements for a large unbiased sample of late B and A stars. Recent work by Abt (1979) has shown that we must accept the fact that some CP stars rotate as rapidly as typical normal (?) late B and A stars.

Ultraviolet spectroscopy of CP stars has provided new insights into both line and continuous spectra. UV spectra will eventually fill in many of the critical gaps that exist in elements identified from ground based observations.

Preston (1974) introduced the notation "CP stars." This useful designation may be used to mean all chemically peculiar stars within the domain of the upper main sequence, including hotter types, which were not discussed extensively by Preston. We shall mention them only briefly in the present article. The qualifying phrase "of the upper main sequence" must be understood by the reader. Carbon stars, barium stars, and G subdwarfs are also chemically peculiar, but they are not " CP stars " in the present sense of the term.

While Preston used the notation CP1, CP2, etc. for different pecularity types, we shall use the more traditional nomenclature. There is some advantage to using a single designation " CP." At some future time, a unifying theoretical concept — perhaps diffusion (Michaud 1980)—may explain these objects. It is premature, in this writer's opinion to assume this. We favour the multiple working hypothesis approach (Chamberlain 1897), and shall refer to Am's, manganese stars, silicon stars, etc. Perhaps this will remind the reader that while there may be a single explanation for these stars, this remains to be seen.

One may distinguish two sequences of CP stars, magnetic and non-magnetic, within which the traditional peculiarity types may be found, These are illustrated in Figure 1, which shows that the different types occur in effective temperature domains. One of the major points that we would like to make in this review is that these temperature domains of peculiarity are enormously influenced by observational selection.

Observational astronomers have not made a clear enough distinction between *peculiarity types* and *abundance boundaries*. It is the latter information that is most important in theoretical work, and it is essential that allowances be made for purely observational selection effects before abundance systematics can be meaningfully discussed. This question will be taken up in detail in the following two sections. In the second part of the paper, we consider the abundance patterns in CP stars, independent of the astronomical setting, and ask if the observations suggest nuclear or non-nuclear patterns.

A more traditional approach has been to consider the chemical anomalies simultaneously with our current understanding of stellar evolution and nucleosynthesis, as well as a host of other properties of CP stars such as duplicity, rotation, cluster membership, etc. While we do not deny the validity and power of this approach, we recognize one major disadvantage. It assumes that all important processes of relevance to our problem are known. Certainly in the case of the heavy elements, this assumption is premature. We shall conclude that *some* CP anomalies "look" nuclear in origin. We eschew an enumeration of nuclear scenarios (such as surface nuclear reactions) and state simply that we do not know how these peculiar abundances came to be in CP star photospheres. But we emphasize that our present inability to suggest a convincing "nuclear" hypothesis is no proof that one does not exist. Nature need not share our ignorance.

II. HOW SHARP IS THE CUT-OFF OF CP STARS IN THE EARLY F'S?

The coolest CP stars have traditionally been found by low dispersion surveys which detect a discrepancy in the spectral type based on the Ca II K line and the hydrogen lines or metallic line spectra. It is not generally appreciated that this task is virtually impossible when the H + H∊ and K lines become comparable in intensity near spectral type F0; this is because the strength or weakness of the K line is estimated with respect to the blend H+He. Recent classification work (Houk and Cowley 1975; Houk 1978; A. Cowley 1976) has revealed a few objects, designated Fm or Del, thought to be decidedly later than the late traditional Am's such as Tau UMa. Are these stars genuinely rare, or are they merely difficult to find? In principle, photometric studies such as the classical one of Stromgren (1963) are relevant. Stromgren discussed a constriction in the m_1 vs b-y plot, which he interpreted as implying a very small dispersion in true abundances. Before this result is accepted, one must ask whether there is anything inherent in the m_1 index that would make it lose sensitivity near F0. While a final answer cannot be given, there definitely are reasons to suspect that m_1 will "saturate" just when the many strong lines of iron group spectra reach the flat part of the curve of growth. According to a preliminary calculation by Kurucz (1979), m_1 does saturate for metal abundances 3 times solar. However, this calculation is very preliminary, and does not yet explain many of the observed properites of m_1. For example, the theoretical m_1's are too small even for the normal A stars, and they provide no insight into the very large m_1's of the classical CP stars. It seems that photometric arguments that the CP sequence does not extend into the F's ((b-y)$\gtrsim$0.02) are yet rigorous. The obvious way to attack the question of the sharpness of the onset of CP characteristics is by high dispersion spectroscopy of a large unbiased sample of early F stars. The study of Gustafsson and Nisson (1972) is of immediate relevance. It shows that a sample of 60 F1—F5 stars is not chemically homogeneous. One star, HR 8220 has [Fe/H] =0.8, and Gustafsson and Nisson raise the possiblity that it may be an Am star. Cowley (1976) classified it a- F2V:, which in our opinion simply shows that abundance anomalies are difficult to detect once the spectrum is very crowded with lines.

We may summarize the ideas of this section by saying that there is little hard evidence that chemical peculiarities end *abruptly* in the early F's. The lack of large variations among late-type dwarfs (cf. Pagel 1979) suggests there is a diminition in both the number and extremity of CP characteristics toward the lower main sequence: detailed features of this diminition are hidden by gross systematic effects.

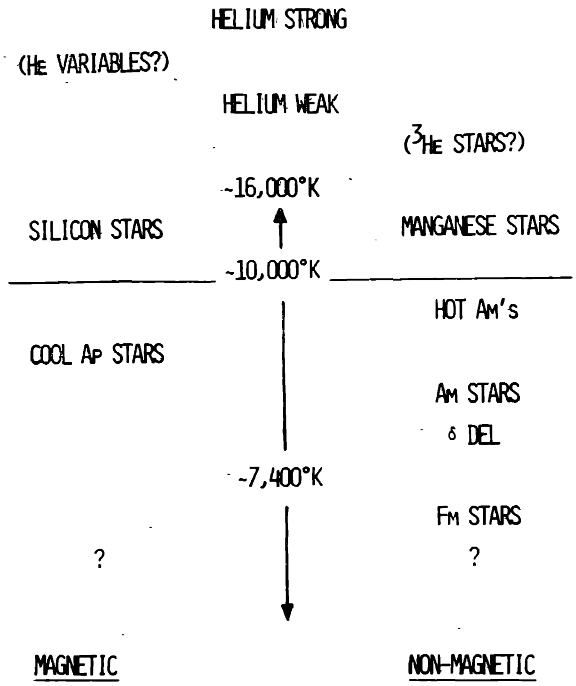
Finally, we note that the continuation of CP characteristics into the lower main sequence is predicted by diffusion calculations of Michaud et al. (1976; see also Vauclair and Vauclair 1977). Early papers on diffusion, both observational and theoretical, overemphasized the sharpness of this cut-off of the CP anomalies at F1 or F2. The existance of late F, chemically peculiar dwarfs is in no way a critical counter to the diffusion theory.

III. OTHER TEMPERATURE DOMAINS AND PECULIARITY TYPES

Since the early work of Morgan (1933) it has been known that the different types of CP stars could be arranged in a temperature sequence. Jaschek and Jaschek (1967, 1974) have discussed this thoroughly, being careful to point out that quite distinct anomalies can occur in stars with almost indentical colours.

In fact, the different peculiarity sub-types are largely defined by the visibility of various atomic features as a function of photospheric temperature. Thus, the confinement of the Am stars to the temperature domain less than about 9500° K and greater than 7400° K is a direct consequence of the fact that this is the region where variations in Ca II K line strengths are most visible. Investigation at coude dispersion (cf. Conti 1965; Conti and Strom 1968a, b) led immediately to the discovery of "hot Am's," from which one may infer a continuation of the *chemical* properties of the Am stars beyond the boundary of the peculiarity type.

Likewise, the confinement of the silicon stars to domains hotter than 10,000°K is related on the one hand to the visibility of the Si II lines λλ4128—4130, and on the other to the visibility of other lines e.g. Sr II λ4077, Eu II λ4129, and several iron group lines which form a blend near λ4170, often attributed to chromium. The Si II lines reach a maximum intensity near



← Fig. 1: The CP Stars. The bifurcation between magnetic and non-magnetic stars is fairly well defined for the stars cooler than 16000° K.

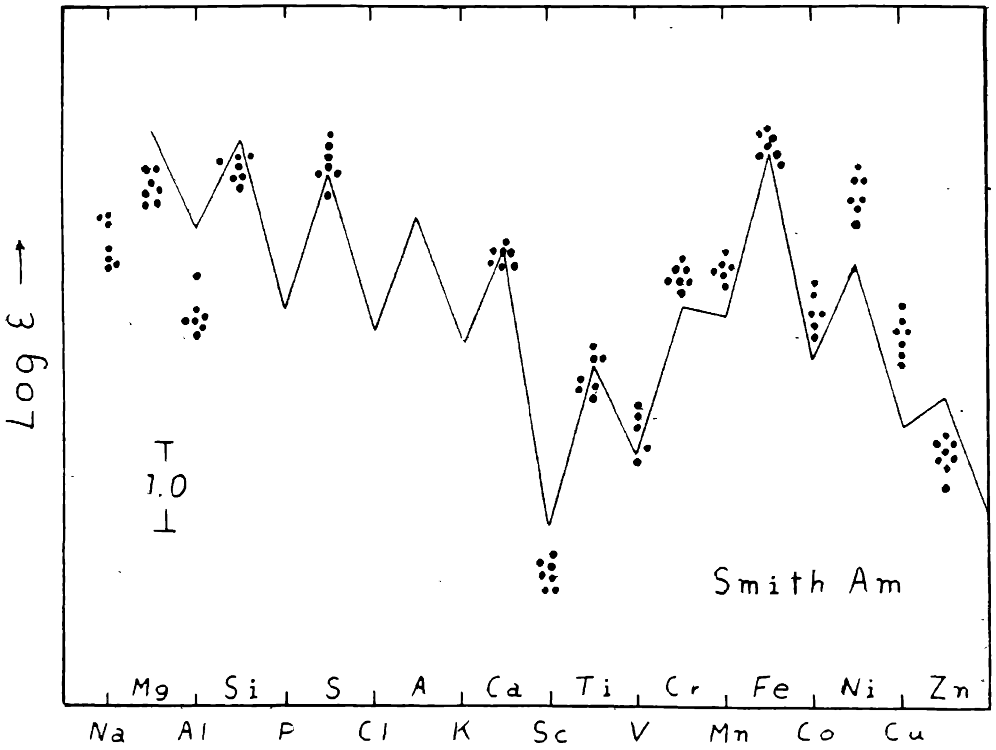


Fig. 2: Smith's data for 32 Aqr, HR 1389, HR 1519, HR 1672, HR 5055, and HR 7850. The solar system abundance pattern (solid line) has been adjusted vertically to fit the stellar data.

A0 V, and are weak (at classification dispersion) by B2. Thus, silicon stars are recognized in the middle to late B's. Although the Si II lines remain visible in the early A's, it is impossible to distinguish Si II λλ4128-30 from Eu II λ4129. Often, a classifier will make the choice between whether to call the star a silicon or a europium star on the basis of his estimate of the stellar temperature ! The cool stars are classified as europium stars.

The helium strong stars are found near B2. This happens to be the spectral type where the He I lines reach their maximum strength. Lines stronger than this maximum are automatically noted as abnormal. Abnormally strong He I lines in a B8 star, for example, could result in a misclassification to an earlier type in all but the most painstaking classification work.

Perhaps the most carefully and thoroughly investigated CP stars are the manganese stars. These objects can not be recognized consistently at classification dispersion; it is something of a tour-de-force that they can be found at all. Higher dispersion is necessary to ensure visibility of the Hg II line λ3984, and Mn II λλ4137 and 4206. Manganese stars can also be recognized at intermediate dispersions from the strong, low excitation lines of Mn II near λ3400 (Osawa 1965). Extensive high dispersion surveys were carried out by Preston (see Wolff and Preston 1978) and Dworetsky (1974, 1976), while Wolff and Wolff (1974, 1976) used the ultraviolet features. Wolff and Preston, and Wolff and Wolff have recently discussed the rotation and duplicity of these stars as a ~~group.~~ ~~Abundance~~ surveys have been carried out by Aller and his coworkers (see Dowretsky 1971), Kodaira and Takada (1978) and Heacox (1979). Aikman (1976), see his ~~Table~~ 4) gives a very useful tabular description of Hg II and Mn II line strengths in a large number of manganese stars.

Wolff and Wolff (1974,1976) demonstrate that the syndrome manifests itself within a restricted domain of effective temperature. Here "syndrome" refers to the presence of unusually strong Mn II lines, typically accompanied by Hg II and, in some cooler objects, by Pt II, in non-magnetic CP stars. A bizarre result emphasized by Wolff and Preston is the unusual strength of Mn II in the hottest Mn stars such as Kappa Cnc. Because of ionization, we would expect the Mn II lines to be fading out in these stars.

While the phenomenology of the manganese stars is surely limited to a special domain of effective temperature, there is no cogent evidence that a manganese *abundance* discontinuity exists. Manganese overabundances occur in both hotter and cooler CP stars (see Hardorp 1966; Hardorp et al. 1968; Bashek 1974; Adelman 1973a, b: Allen and Cowley 1978). The hot star 3 Cen A shows the high excitation phosphorus and gallium lines which are also found in many manganese stars; it is quite natural to assume that the chemical peculiarities of the manganese stars continue at least into these helium weak stars, with temperatures just below 20,000°K.

At the cool limit of the manganese stars, there is no obvious "type" of CP star into which the manganese stars pass. Chemical similarities, strong manganese and platinum (cf. Cowley 1977) are found among CP stars of the magnetic sequence. It is usually assumed that the hot Am's and traditional metallic line A stars continue the Mn star sequence, but the necessary "missinglinks," that is, platinum or mercury-manganese Am stars, have not been found. We can immediately suggest selection effects which would make this difficult.

In their work on ^{3}He, Hartoog and Cowley (1979) reported subtle fine structure in the helium phenomena. The stars with ^{3}He were found in a small domain of colour between the helium strong B stars and a group of helium weak stars without ^{3}He. Their sample of helium weak stars is too small (18) for this fine structure to be established with high statistical confidence. However, they did find a highly significant (>99% confidence) relation between the ratio ^{3}He/(^{3}He+^{4}He) and the unreddned Stromgren c_1 which supports the contention that the ^{3}He anomaly reaches a maximum in the hotter helium-weak stars. It wouls be well to investgate a wider sample of stars, and to search for possible systematic effects which might make the ^{3}He/ (^{3}He+^{4}He) ratio decrease as the strength of He I decreases toward cooler stars. With these caveats entered, we feel the ^{3}He systematics deserve careful consideration as indicators of true abundance boundaries

We have seen that in many cases the sub-classes of CP stars occur in limited temperature domains (see Fig. 1) for reasons completely related to the visibility of certain spectral features, ~~quite~~ independent of stellar abundances. In other cases, it is necessary to show that systematic effects are not present before one can accept that the sub-type boundaries are really abundance boundaries.

It does not seem plausible that *all* of the sub-type boundaries fail to reflect abundance differences—some real abundance boundaries are probable. But it does appear to this writer, that the picture of the abundance sub groupings of CP stars will eventually be quite different from the one many of us have today.

IV. ABUNDANCE SYSTEMATICS: INTRODUCTION

The overall abundance systematics of CP stars have been discussed in the papers listed in Table 1 and elsewhere, so we need not attempt a general discussion here. One of the salient features of these abundances is the deficiency of helium and oxygen simultaneously with excesses of trace elements such as the lanthanides. This kind of a pattern is straightforward to interpret if radiation pressure acting primarily on the spectral lines is responsible for the upward thrust, which may effectively counter gravity. If the number of atoms per cubic centimetre is relatively high, as in the case of helium and oxygen, the strong atomic lines are saturated, little radiative flux passes through them, and the consequent upward force is small. Such elements might be expected to seek a scale height commensurate with their atomic weight, which means that they would sink in the hydrogen matrix of the stellar atmosphere. Trace elements will, by definition, have weaker lines, and can be forced upward.

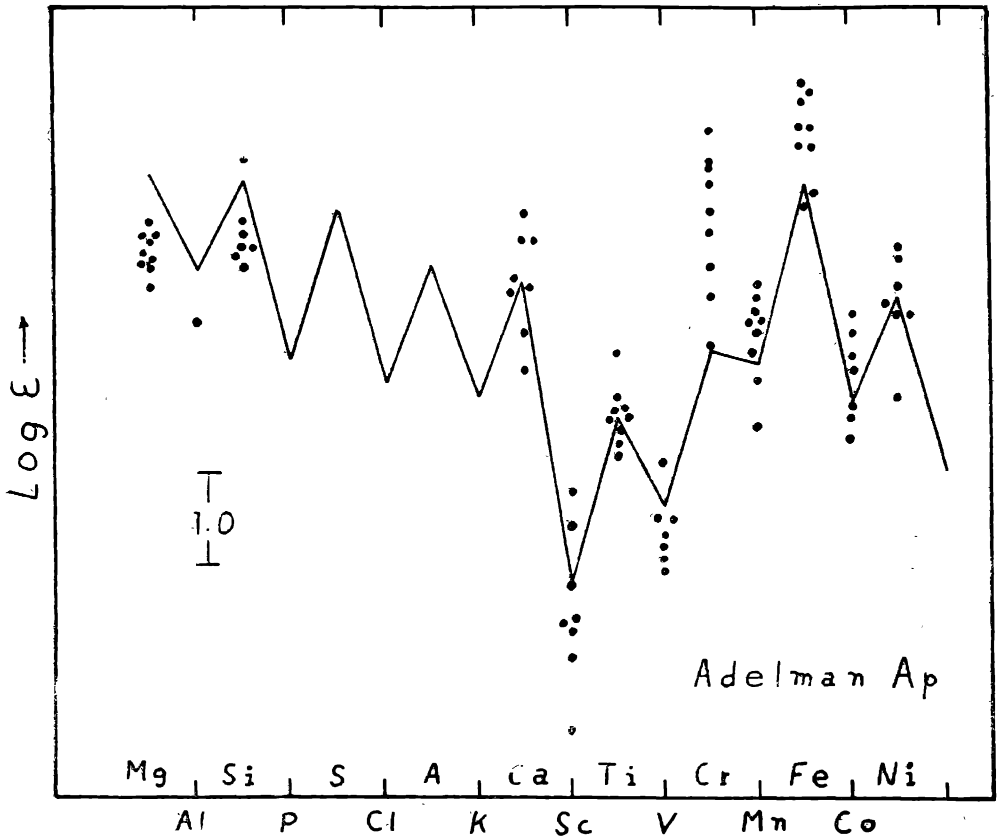


Fig. 3: Adelman's data for 10 Aql, BCrB, 33 Lib, 78 Vir, HR 4816, HR 4854, HD 165474, and HD 191712. Aller's abundances for the rare-earth maximum of HR 465 are also plotted. This star has the lowest of the Cr abundances; abundances for the other elements are typical. Solar abundance as in Fig. 2.

While this picture can break down when applied to individual cases — specific elements in specific stars — its general validity is a strong argument that the diffusion mechanism is operating in CP stars.

If diffusion is the primary cause of the CP anomalies, it appears, at least to this writer, that the relevant astrophysics is generally known, although certainly not in detail. By contrast, convincing astrophysical scenarios for nuclear processing which might cause such abundance anomalies remain to be worked out. In what follows, we shall nevertheless refer to abundance patterns which "look nuclear," leaving entirely open the astrophysical processes which gave rise to them. That such an approach is possible was demonstrated by Suess and Urey(1956) in their treatment of solar system abundances. In the introduction to this classic work, the authors reviewed some of the history of abundance compilations, pointing out that " ... one observation ... proved to be of fundamental importance in many fields of science. It was that expressed by Harkin's rule which states that elements with even atomic numbers are more abundant in nature than those with odd ones."

In the discussion of CP stars which follows, we focus on abundances of contiguous elements which are capable of showing departures from this odd-even abundance alternation that are most easily understood in terms of nuclear systematics. We divide the discussion into several categories. First, we discuss the abundances of elements sodium or magnesium through the iron group (Sc — Ni). Most of these elements have reasonably well determined abundances, at least relative to one another. In the case of some of the older work, it is necessary to ~~apply~~ corrections for revisions of the gf-value scales. Uncertainties resulting from these corrections, as well as other errors, certainly amount to factors or two to five. We believe that the relative errors are not much larger than this, at least for these intermediate and light elements. These particular elements have better erlative abundances than, for example, the rare earths for several reasons. More effort has been put on them by abundance workers. The spectra are more familiar, both in the laboratory and in the stars, and atomic data have been more available.

The second category of elemental abundances consists primarily of yttrium and the rare earths. These elements share the common denominator that their abundances are far less accurately known. The laboratory and stellar spectra are less familiar. Lines have been misclassified, excitation and ionization potentials unavailable, transition probabilities unknown etc. etc. The situation has improved markedly in the last decade, but there are still critical gaps. Very few abundance studies have been done recently enough for the authors to have benefitted from the latest improvements in atomic data for the rare earths. Another difficulty is the fact that the observed ionization stage is frequently present only in minute fractional amounts. Abundances in silicon and manganese stars are dominated by ionization corrections. We have suggested (Cowley and Aikman 1980) that the observations may reflect a breakdown of the Saha equation, or alternately, the existance of much cooler boundary layers that are not included in traditional model atmospheres. Finally, for the lanthanides, we often find that the results of our own work on wavelength coincidence statistics do not agree with published abundances. In some instances, we have been able to find the cause of the discrepancies. Cowley and Arnold (1978) document a number of cases where supposed rare earth lines were actually due to Cr I and II. As a result of such considerations, we have reached the conclusion that published relative abundances of yttrium and the lanthanides are often *totally unreliable*. We therefore warn the readers that *our* judgements concerning abundances of these elements may conflict severely with impressions that may be drawn from a number of papers, as well as upon reviews which have drawn on this basic material (cf. Preston' (1974) , Figure 7).

The final category of abundance we shall discuss consists of certain cases which this reviewer finds overwhelming. We have argued (Cowley 1980) that most rare earth excesses may be no more than two orders of magnitude. In the cases of mercury and platinum, there are no plausible ways of avoiding excesses of 4 — 6 dex. Several elements, in addition to mercury and platinum, fall into this third category. The strangest of all is gallium.

V. SODIUM THROUGH THE IRON GROUP

Figure 2 shows a plot of abundances from Smith (1971). The following adjustments have been applied to his abundances in an attempt to correct for old gf-values:—Cr: + 0. 1; Mn: + 0. 6; Fe: + 0. 8; Ni: + 0. 9. The abundances in these stars are generally similar to one another, and we have not plotted all of Smith's data. The "solar" abundances from Cameron (1973) are shown by the solid line.

This material shows that the abundance pattern in the Am stars is very similar to that in the solar system. The odd-even effect is marked. If we knew nothing about the Am stars other than this abundance pattern, we would surely conclude that the pattern is basically nuclear in origin, just as the solar pattern is, and that only mild changes have taken place.

In Figure 3, we show abundances for several of Adelman's (1973 a, b) Ap stars ; again, we have not plotted all of the available data. These stars have effective temperatures which are similar to those of Smith's Am stars. The abundance patterns show larger departures from solar than the Am's. Chromium shows excesses up to a factor of 100. Note that the odd-even effect is still well preserved, and that scandium shows a marked deficiency in some, though not all of the stars. The mechanism responsible for the peculiarities shown here must be capable of changing chromium by as much as two orders of magnitude while limiting the other relative abundances to much smaller amounts, and preserving the odd-even effect.

Figure 4 is a plot of abundances in the manganese star primaries of HR 4072 and χ Lup, as reported by Dowretsky (1971). We consider the abundances for these stars to be well determined. These cool manganese stars have mild manganese anomalies, *even though* they ave extreme platinum and mercury excesses.

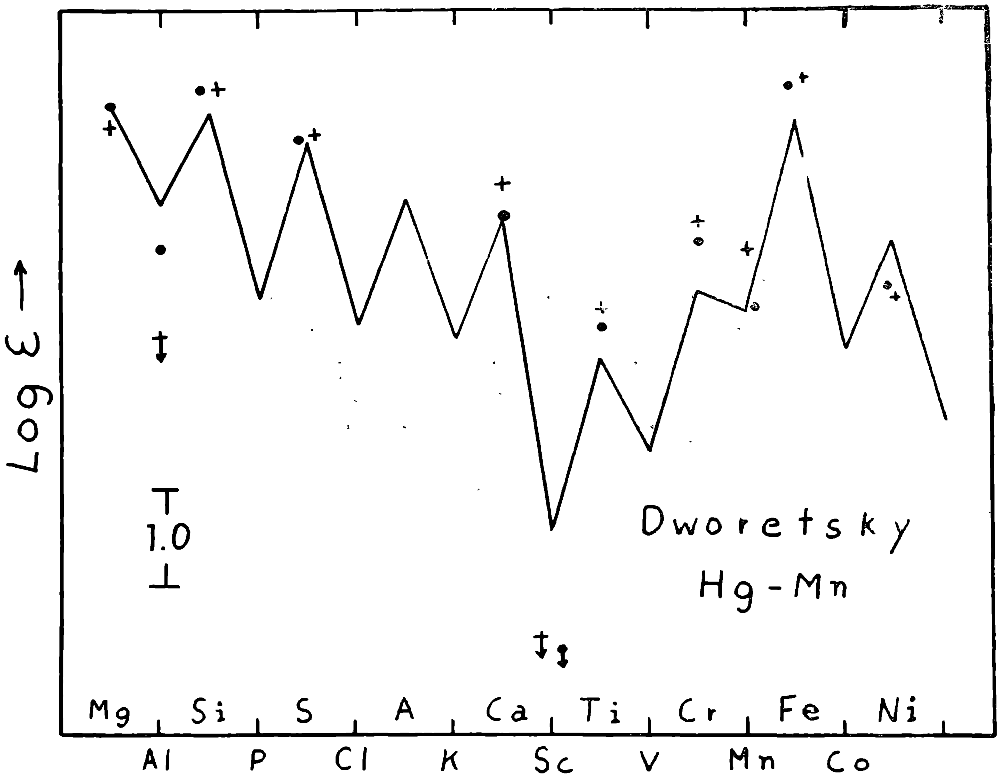


Fig. 4: Dworetsky's data for the cool manganese star primaries Chi Lup (dots) and HR 4072 (plus signs). The scandium points are upper limits. Solar abundances as in Fig. 2.

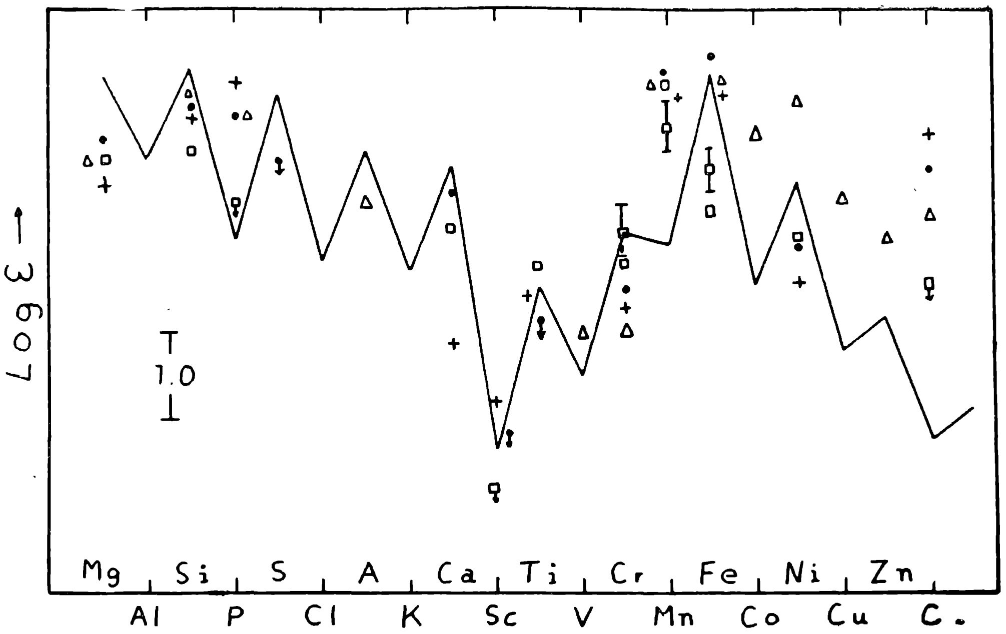


Fig. 5: Heacox's abundances for the manganese stars 53 Tau (squares) and HR 7361 (points), and Aller's abundances for Kappa Cnc (plus signs). Allen and Cowley's Cr, Mn and Fe abundances for 53 Tau are shown with error bars. Abundances for 3 Cen A (triangles) are from Hardorp et al. or Hack and Stalio. Solar abundances as in Fig. 2.

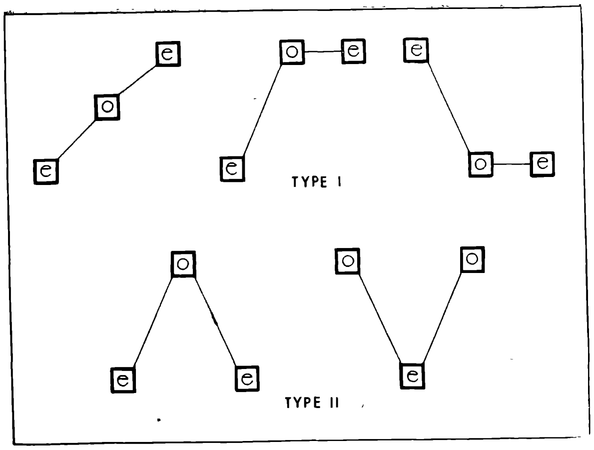


Fig. 6: Abundance patterns which violate the odd-even effect.

In Figures 2-4 we see that the elements Na-Ni show abundance patterns that are entirely compatible with nuclear systematics. In the Am stars, this may be true of all their abundances.

Figure 5 shows abundances taken from Aller (1970) for *k* Cnc and Heacox (1979) for 53 Tau and HR 7361. All are extreme manganese stars. 53 Tau has an intermediate temperature, while the two other stars have temperatures near the top of the range for this peculiarity type. The abundances for 3 CenA are from Hardrop et al (1968) and Hack and Stalio (1976).

Following Guthrie (1971a, b) and others, this writer has placed special emphasis on departures from the odd-even effect as indicators of non-nuclear processes. We distinguish between Type I and Type II anomalies as shown in Figure 6. Some nuclear processes give rise to Type I anomalies; we know of no nuclear process give rise to Type I anomalies; we know of no nuclear process of possible relevance to stellar abundances that would give a Type II anomaly.

The star 53 Tau has an apparent Type II odd-Z anomaly at manganese. This effect was found by Allen and Cowley (1978), whose abundances for Cr, Mn, and Fe, are shown along with their error bars. Recently, we (Cowley and Aikman 1980) have taken a somewhat guarded position in this particular odd-Z anomaly, until such a time as the error bars between iron and manganese are farther apart. However, several other workers who have studied 53 Tau (cf., e.g. Wolff 1967; Jamar et al. 1978) have noted the weakness of iron. There can therefore be no doubt that in this star the Fe / Mn ratio is unusually low.

In Figure 5, we also note that the odd-even effect is strongly perturbed at phosphorus and probably gallium. Surely, these abundance patterns differ significantly from solar, and in a way that is not easy to understand in terms of nuclear processes.

VI. YTTRIUM AND THE LANTHANIDES

Yttrium is typically strong in the manganese stars. This writer was astonished to find Y II 4177 stronger in θ Her than the Sr II resonance line 4077. However, Allen's (1977) thorough study showed that while the abundance pattern in θ Her and other manganese stars was surely perturbed from solar, the anomalies were found to be Type I rather than Type II.

Yttrium is readily identified in the cooler magnetic CP stars, but is characteristically weak in many (not all !) of the hotter magnetic stars. This is puzzling, because many of these same hot, magnetic stars have rich lanthanide spectra, and one would expect to see yttrium along with these lanthanides, since their atomic properties are similar.

Here we shall discount all quantitative abundance studies for yttrium and the lanthanides for stars hotter than 11,000 °K, because we have reason to suspect that the traditional LTE analyses may not be valid. We shall rely primarily on the qualitative element identification results obtained by Aikman, Cowley, and their coworkers using the method of wavelength coincidence statistics (WCS). Other identification work has been used only when it is in good agreement with the WCS.

It is not our intention to question the validity of many competent published qualitative identification studies in the sense that we have cast doubt on the validity of most quantitative lanthanide abundances. However, our work has the advantage that a large number of lanthanide-rich stars have been treated uniformly, with modern wavelength lists. This gives us a very good insight into the relative strengths of different atomic spectra in these stars. For example, reading the identification work of Adelman et al. (1973) on β CrB, one gets no impression of the neodymium-samarium "hole" (see below) that makes the rare earth pattern in this star so unusual. We do not deny the *presence* of Nd II or Sm II in β CrB, but *relative* to the lanthanidet pattern in *most* cool CP stars, there is no question that these two spectra are unusually weak.

The present writer and his colleagues have discussed the systematics of the lanthanides in several papers (see Cowley 1976, 1978 ; Cowley and Henry 1979). The purely empirical two component model, which we discussed in 1976, remains the basis for a useful description of rare earth systematics. The most common pattern is dominated by Ce II with the spectra of the intermediate and heavier lanthanides steadily weakening in *most* stars. This is the pattern due to what we have called "Component A." A few stars have unusually weak Ce II with the simultaneous presence of intermediate and heavier lanthanides. Typically Eu II dominates. This pattern we attribute to "Component B.". In some stars, both components are present (see Figure 7).

In a few stars, Eu II is so strong that there is the possibility that an odd-Z anomaly may exist. This is apparently the case in β CrB (Adelman 1973a, b) and 73 Dra (Sadakane 1976). Reliable Eu abundances are most difficult to obtain because the gf-values are not accurately known, and because the lines show broad hyperfine structure. It must be noteed, that neither of these stars have typical lanthanide patterns. All lanthanides, other than europium, are weak in 73 Dra, while β CrB has a pronounced neodymium-samarium "hole," with very strong cerium, europium, and gadolinium.

If we restrict our attention to the cooler CP stars, where the dominant lanthanide lines are the readily observable, singly ionized species, then we find that typical line strengths are comparable in both Ap- Am stars. In our opinion, abundances of cerium and lanthanum are therefore comparable in cool Ap and Am stars, and the abundance excesses are rarely more than two orders of magnitude. Some systematic differences exist between the Am's and the Ap's. For example, Eu II is typically stronger in certain magnetic CP stars, as though there were often an admixture of " Component B". The Am spectra generally show only " Component A", i. e. normal patterns.

It is our opinion that when reliable lanthanide abundances become available, the resulting patterns will generally reflect the odd-even effect, as would be expected from nuclear processes. However, a few stars may show definite departures, most probably at europium.

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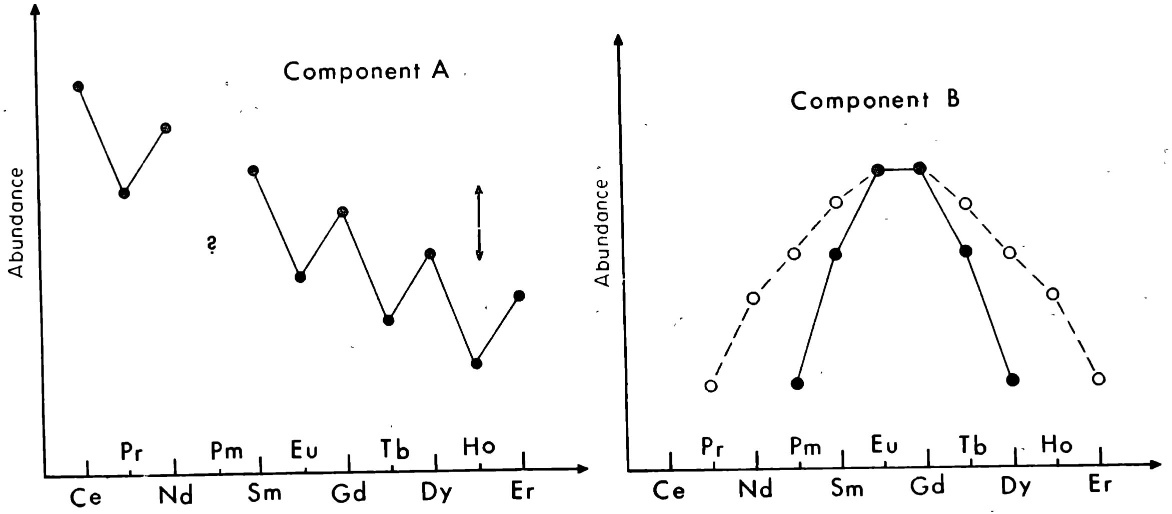

Fig. 7: Empirical two-component model of lanthanide abundances in CP stars. Component A is the most typical pattern. The heavier lanthanides are often below the detection threshold indicated by the double-headed arrow. Both the location and breadth of the maximum of Component B are variable.

VII. THE EXTREME ANOMALIES

It would be easier to understand the CP stars if we could somehow dismiss ^{3}He, gallium, platinum, and mercury as observational errors : misidentifications perhaps. This is not possible. In the cases of Pt II and Hg II, we have independently derived abundances with results in good agreement with those of other workers. Recent work on the oscillator strengths of Hg (Dworestsky 1980), and in the ultra-violet (Megessier et al. 1980: Leckrone 1976, 1979 ; Guthrie and Stickland 1980) strengthen the general picture. There may still be some possibility of constraining these enormities to the Hg-Mn stars, but our own work, as well as that of Adelman (1974), Pyper (1976), etc. suggests that both mercury and platinum may be found in the magnetic stars.

If stellar photospheres are chemically differentiated from the solar abundances, a useful concept is the "degree of fractionation." Mercury and platinum, with their excesses of 10^4 — 10^6, are far more highly fractionated than the iron group. It is reasonable to assume that when mercury and platinum can exhibit extreme fractionations, other elements may do so too. It then becomes difficult to understand how the mercury and platinum excesses in χ Lup and HR 4072 can be accompanied by such *mild* departures from solar patterns as was illustrated in Figure 4.

VIII. EXPECTED CORRELATIONS

An overall regularity that can be noted in the solar abundances is the **correlation** of the elements with each other. There are, of course, well known signatures of various nuclear processes : the Sc trough, the Fe peak, r and s process peaks, etc. And, of course, the ubiquitous odd-even effect. Apart from these things, the abundance of an element Z is highly correlated with the abundance of elements Z + 1 and Z — 1. The reason is that the elements were built up, by nuclear processes, in which a given species was closely coupled to other species with similar masses.

Non-nuclear processes reflect regularites in *atomic* structure which *sometimes* correlate with nuclear properties, but often do not, This means that in a diagram in which abundance is plotted vs. Z, one could expect correlations of abundances for elements with widely separated Z. Such correlations might recur with the well known periodicities of atomic structure, but in the present context, we do not know enough about the relevant processes to *demand* such discontinuities.

Looking over the abundances in the CP stars that are presently available and trustworthy, we see several features which suggest non-nuclear mechanisms. The most prominent, in our opinion, has been the gallium anomaly. However, we need more detailed information about the neighbouring elements zinc and germanium. Zn III has been identified in 3 Cen A by Hack and Stalio (1976), who derive an abundance of 6.2 (log H = 12) from λ1146.1. Hardorp et al. (1968) give 6.2 for the logarithmic gallium abundance. These abundances must be regarded as very preliminary, but we have no basis here for concluding that there is a definite Type II odd-Z anomaly at gallium in 3 Cen A. The Hack-Stallio abundances change smoothly from iron through zinc. The abundance pattern is definitely non-solar, but it is not incontrovertibly non-nuclear (see Fig. 5).

The appearance of gallium seems to be correlated with that of phosophorous. In 3 Cen A, and other helium weak B stars, we have phosphorus, gallium, *and* ^{3}He. Correlations of this kind, are difficult to relate to nuclear processes.

It is not possible to make a case that the appearance of mercury and platinum are always correlated with manganese. The strongest platinum star that this writer knows of is HR 7775. Although it has strong yttrium and mercury, it is *not* a manganese star. Indeed, we have sometimes described it as the mirror image of the extreme manganese star 53 Tau. HR 7775 has Ga I and Ga II, but P II has not been found. The star may be too cool for P II, so it would be of great value to attempt to identify phosphorus from ultraviolet or red spectra.

The star HR 7775 illustrates another conundrum. Why are the heavy elements platinum and mercury found in stars, usually the manganese stars, in whose spectra the lanthanide rare earths are generally absent ? Why is there such a big gap between the oveaboundant yttrium and / or zirconium and the overaboundant platinum and mercury ? Recently, Aikman and Cowley (see van den Bergh 1979) identified gold, the odd-Z element between platinum and mercury, in HR 7775, This appears to be mild support for a nuclear pattern. One can say that the gold, being odd-Z, is expected to be less abundant than its even-Z neighbours, and we have found it only in the most *extreme* Hg-Pt star. However, it can also be argued that the diffusion theory would predict the simultaneous occurrence of these elements, since, in being pushed up from substantial depths, all three elements would pass through a sequence of identical isoelectronic states.

IX. HR 465

The rare-earth maximum spectrum of HR 465 is distinct among the CP spectra that this writer has examined. We suggest that it may be a phase in which the influence of non-nuclear pattern is minimized. Let us list below some of the unusual abundance properties of HR 465 which point to nuclear processing :

(1) Throughout the domain of abundance determinations (Aller 1972 ; Cowley 1976) there is no promising case for an odd-Z anomaly, even though departures from solar abundances are undenia bly large.

(2) More contiguous elements are observed in this CP spectrum than in any other. Many of the common lanthanides are unusually strong, and intermediate and heavy lanthanides are also well identified. It is straight forward to interpret this in terms of "nuclear" correlations.

(3) The mssing lanthanides, La, Pr, Tm, and Lu have odd-Z.

(4) There is a decided decline in abundance from a maximum at Nd and Sm toward the lighter elements Ce, La, and Ba, the latter of which cannot be identified with confidence. In the comparable region of the nuclide chart, near the $N = 50$ shell closing, analogous behavior may be seen. Molybidenum and niobium are unusually strong, while yttrium is weak or absent and strontium, though present, is not strong as it can be in many magnetic CP stars.

(5) There is good evidence for merucury, platinum, and osmium, the even Z elements from the $N = 126$ r-process peak. Hf II, W II, and Re II have also been identified in our recentt work on HR 465. We have, then, good evidence that the appearances of all these heavy elements are correlated with one another.

(6) Thorium and uranium can be identified. The statistical confidence for uranium is extremely high (99.99%), and the fact that this occurs at a phase when Cr I is weak strengthens the identification further (see Cowley and Arnold 1978; Cowley et al. 1977). Thus the correlation of heavy elements continues through these actinide rare earths.

The only standard process of nucleosynthesis that is capable of making uranium and thorium is the r-process, since they are heavier than the last alpha-stable element bismuth. Their presence in HR 465 therefore suggests the r-process (Cowley et al. 1973). There are a variety of other abundance systematics which suggest the r-process : the weakness or absence of Ba, Sr, and Pb with the simultaneous prominence of species such as Eu and Ho, which have large neutron capture cross sections. This writer has studied abundances in Ba II stars, where the pattern is surely due to *slow* neutron addition. In the Ba II stars, europium is weak, while praseodymium is outstanding in strength. We find just the opposite in HR 465.

Several workers have suggested fission as an explanation of CP abundances (Kuchowicz 1976 ; Ohnishi 1975 ; Steinberg and Wilkins 1978). The notion that an r-process is involved dates from the early work of the Burbidges and their collaborators (see Fowler et al. 1965). We refrain from comment on the relative merits of these ideas, and emphasize overall impression of nuclear systematice gained from abundances in this star and to a lesser extent, in other CP stars.

X. WHAT MAKES CP STARS ?

There are many ways of doing science, and a general formula that leads to success cannot be given. A popular ploy among observers is to set out a list of phenomena " which any successful theory must satisfy." While this is often a useful approach, it is not always the best one. It may be that with the CP stars, the overall problems are simply beyond our present abilities to solve, while lasting and useful solutions to specialized problems can nevertheless be made.

Without doubt, the diffusion hypothesis is in best accord with the majority of " facts " about CP stars as we think we know them today. The facts are explained in terms of plausible physics with a minimum appeal to unknown mechanisms. If there could be only one theory allowed to us, it would, on the basis of everything we think we know now, surely have to be diffusion. We shall not elaborate upon the strengths of the diffusion hypothesis since they have been ably expounded by others. It does seem useful to point out that if diffusion, appropriately modified by such factors as rotation and magnetic geometries, can be established as the dominant cause of CP anomalies, we will be able to probe the hydromagnetic *history* of stellar envelopes by observing the surface chemistry of the stars. This is an exciting prospect.

Our position is that there probably is no single explanation of all of the chemical anomalies. We remain impressed with the difficulty of establishing a genuine, credible, Type II odd-Z anomaly, and the overall correlation of *adjacent* elemental abundances. These observations suggest that differentiation has not, in most cases, erased the nuclear signature of the primitive abundance pattern. It must be emphasized that our understanding of the origin of elements beyond the iron peak is rudimentary. While the r- and s- processes are well established from the systematics of solar system abundances, there is still some difficulty with the astrophysics of the s- process. The circumstances under which the r-process occurs are an even greater unknown.

Basic data on the elements created by these neutron addition processes is primarily limited to the solar system. Beyond this, the CP stars are probably the richest source of information on the cosmochemistry of the heavy elements.

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