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NUCLEAR AND NONNUCLEAR ABUNDANCE PATTERNS IN THE MANGANESE STARS*

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ABSTRACT

The manganese stars show abundance anomalies that are in conflict with the predictions of nuclear astrophysics. We stress the deviations from the odd-even effect that occur for phosphorus, gallium, and yttrium. The abundance anomalies (e.g., the Mn/Fe ratio) in the iron peak are less serious; within the uncertainties of the current determinations, they may be explained in terms of the same processes that predict the solar-system abundances.
Subject headings: abundances, stellar — nucleosynthesis — peculiar A stars

I. INTRODUCTION

In the past few years, promising nonnuclear hypotheses have been developed to explain abundance anomalies in early-type stars (cf. Michaud 1970; Havnes and Conti 1971). These ideas were developed in response to the difficulties of explaining the abundance anomalies within the context of nucleosynthesis in apparently unevolved stars.

The difficulties with nucleosynthesis are to a large extent a function of the "boundary conditions" that are imposed. These conditions are frequently more detailed than those applied in the case of the solar system, where the primary effort has been to find a sequence of temperatures and pressures that will explain the observed abundances. Much less thought has gone into the question of how the products of the *p*-, *r*-, *s*-, etc., processes come together to give the observed mixture.

By contrast, stellar abundance workers frequently demand a *connection* between the abundance anomalies of elements, such as silicon and the rare earths, which are usually thought to be due to quite distinct processes. There is, moreover, some compulsion to attempt a detailed, if qualitative, integration of the nucleosynthesis into the framework of stellar evolution.

We should like to call attention to a particular kind of abundance pattern that poses grave difficulties for any nuclear theory, quite independent of such "boundary conditions." Such a pattern occurs when an element of odd atomic number Z has an abundance that is greater than that of the adjacent elements with even Z.

The tendency of elements with even atomic number to be more abundant than their neighbors with odd Z is an extraordinarily marked characteristic of the solar system abundances. This odd-even effect owes its existence to the pairing energies of nucleons—a fundamental property of the atomic nucleus. It is to be expected whenever nuclear forces are primarily responsible for cosmic abundances. In this sense, it is more fundamental than the "peaks" of the theory of nucleosynthesis, which only appear with a particular process. Deviations from the odd-even effect may be taken as good evidence for nonnuclear processes.

The best examples of deviations from the odd-even effect occur in the manganese stars, and the best case is probably the yttrium to strontium and zirconium ratio. In what follows, we shall discuss abundances found by other workers, chiefly Aller and his colleagues, but we shall confine our discussion to stars that we have studied for element identifications using 2.4 Å mm^{-1} plates taken at the Dominion Astrophysical Observatory (DAO).

II. THE YTTRIUM ANOMALY

Abundances for strontium, yttrium, and zirconium are shown in table 1 for the manganese stars ϕ Her and ι CrB. The strontium abundance has been adjusted from the value reported in the references, since the experimental *gf*-values adopted there were affected by self-absorption. We adopt log $gf = 0.1$ and -0.2 for $\lambda\lambda$4077 and 4215.

We are in the process of a detailed study of the abundances of "critical" elements in these and a number of other manganese stars, but preliminary work shows little likelihood that the yttrium abundance could be reduced to the point where the anomaly would no longer exist. Even a visual inspection of our plates of ϕ Her shows the Sr II resonance lines to be weak in comparison with a number of Y II lines. There can be no question of the identification of these lines, nor is there any possibility that chance blends could increase the strength of so many strong features. We have considered hyperfine structure, oscillator strengths, and the degree of ionization as possible

TABLE 1

LOGARITHMS OF Sr, Y, AND Zr ABUNDANCES

	Sr	Y	Zr	Reference
ϕ Her.......	3.5	5.3	4.1	Zimmerman *et al.* 1970
ι CrB.......	3.4	4.5	3.4	Ross and Aller 1970

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sources of error, and concluded that none of these factors could change the Y/Sr ratio by the large amount necessary to remove the discrepancy in ϕ Her.

The abundance of zirconium has possibly been underestimated—we say this simply because the *gf*-values are not as well known as those of strontium and yttrium. However, a nuclear process that would give the abundance pattern Sr < Y < Zr would almost certainly produce observable amounts of niobium and molybdenum, and these elements are not observed in the manganese stars.

III. THE PHOSPHORUS AND GALLIUM ANOMALIES

Two additional conflicts with the odd-even effect occur in the manganese stars at phosphorus and gallium. We shall report the results of our own statistical investigations of phosphorus and sulfur in five manganese stars, because the abundance data are exiguous. Our material has the advantage of completeness and uniformity, and is adequate for the present purposes, since it shows that it is possible to identify both phosphorus and sulfur in stars of similar temperatures and gravities. In the spectrum of ϕ Her, we can identify sulfur but not phosphorus, while in that of ι CrB the situation is reversed. In the spectrum of the hotter star κ Cnc, phosphorus lines are present in profusion, while the sulfur lines are weak or absent. The ionization potentials would lead us to expect sulfur rather than phosphorus in this spectrum. Aller (1970) found a very high abundance of phosphorus, while sulfur was not studied, presumably because its lines could not be found. In this case we clearly may conclude that phosphorus is more abundant than sulfur, and, with care, other qualitative conclusions concerning abundances may be drawn from the data in table 2.

The element-identification program was discussed by Hartoog, Cowley, and Cowley (1973) to whom we refer for details. The program investigates the statistical significance of H coincidences or "hits" within a tolerance window w, which is usually chosen to be ± 0.06 Å. The N strongest laboratory lines are selected, and the coincidences with them are compared with coincidences on (usually) 200 sets of N nonsense wavelengths. The result of this Monte Carlo procedure that has the most meaning is the fraction of times f that the number of coincidences obtained for the nonsense wavelengths was equal to or greater than those obtained for the laboratory wavelengths, since it is an approximation to the probability that the coincidences with the laboratory set are due to chance. However, when f is very small, a large number of trials with nonsense wavelength sets is necessary to determine it accurately. Consequently, we also compute a parameter s (we use a lower case s to avoid confusion with the chemical symbol for sulfur), which gives, roughly speaking, the "significance" of the result in standard deviations (cf. Hartoog *et al.* 1973). Some care must be used in interpreting this parameter, though, because the statistics are frequently far from Gaussian.

Four of the stars in table 2 were investigated on DAO plates. The results for HR 4072 are in press (Cowley *et al.* 1974). The stars are arranged in order of effective temperature, as determined in abundance studies: the reference for π^1 Boo is Montgomery and Aller (1969); for HR 4072, Guthrie (1966).

No nuclear reactions that even approach equilibrium will predict more phosphorus than sulfur. Aller's (1970) study of κ Cnc gives P $\geq$ Si, a completely perverse situation. It is as though the decay channels of the compound nucleus $^{32}S^*$, the intermediate result of $^{16}O + {}^{16}O$, were manifested in the Si, P, and S abundances in κ Cnc (cf. Spinka and Winkler 1972). The possibility that the *direct* products of $^{16}O + {}^{16}O$ might be related to stellar abundances does not seem to have been seriously considered. Silicon-28 is thought to be the dominant product of oxygen burning. Yet perhaps some consideration *should* be given to nonequilibrium processes. For this reason we feel that the odd-Z anomaly at phosphorus is not quite so incisive as at yttrium.

Certainly one of the most bizarre identifications in the entire domain of peculiar A stars is that of Ga II in the manganese stars (cf. Bidelman 1960). Although the importance of this discovery has long been known, it does not seem to have been discussed in the context of the odd-even effect.

The probability that gallium is misidentified is small. Our results for κ Cnc are as follows, based on measurements of 362 lines in the wavelength region 3780–4635 Å. All four Ga II lines listed by Bidelman and

TABLE 2

COINCIDENCE STATISTICS FOR PHOSPHORUS AND SULFUR*

	P II $(\chi_{I}, \chi_{II}) = 10.5, 19.7$			S II (10.4, 23.3)		
STAR	H/N	f	s	H/N	f	s
κ Cnc..........	19/26	< 0.005	+16.3	1/22	0.72	−0.02
π^1 Boo.........	6/28	< 0.005	+ 3.8	8/22	< 0.005	+6.1
ϕ Her..........	2/28	0.82	− 0.6	11/22	< 0.005	+5.5
ι CrB..........	10/28	< 0.005	+ 4.7†	2/22	0.55	+0.5
HR 4072.......	4/32	0.15	+ 1.4	7/24	0.03	+2.4

* First and Second ionization potentials are given.

† At $w = \pm 0.04$, $s = 6.5$.

Corliss (1962) were measured. With $w = \pm 0.06$, $f = 0.0012$; with $w = \pm 0.04$, $f = 0.0003$. These figures are based on 10,000 Monte Carlo trials.

Aller's (1970) values for the abundance of gallium in κ Cnc is comparable to that of iron! Although it is possible that this situation might arise under conditions of very high density, or by addition of neutrons to the iron peak nuclei there is no way that the odd-Z element gallium could be more abundant than zinc or germanium. There may be some possibility that our failure to detect these elements is due to their atomic properties, which are much less well known than those of strontium, yttrium, and zirconium. For this reason, we believe the yttrium anomaly to be more clearly demonstrated than that of gallium, but the latter is potentially a very strong case.

IV. SILICON AND THE IRON PEAK

It is interesting to examine the run of abundances in these stars from silicon through the iron peak. We do not feel that the manganese abundance presents a strong case against nucleosynthesis. Most of the abundances that can be found in the literature predate the revision of the f-value scale, which affected both Fe I and Fe II. Consequently, all of the iron abundances must be reconsidered. We cannot make revisions (as in the case of the Sr II lines) without a careful examination of a large number of iron lines in each spectrum, but certainly all of the iron abundances will increase, probably by factors between 2 and 10. Thus, there is no necessity to conclude that Mn/Fe > 1 in any star, although some of the stars (e.g., 53 Tau) showing very high values of this ratio should be carefully reexamined.

In ι CrB the abundances from silicon through the iron peak are quite similar to the predictions of silicon-burning quasi-equilibrium. Figure 1 shows a comparison of the observations with theoretical predictions that we have made following the method of Bodansky, Clayton, and Fowler (1967). With the possible exception of Ni, which we shall discuss below, the fit is promising, especially when we consider the uncertainties of the stellar determination. The theoretical calculations, incidentally, were not optimized for the ι CrB data, but were made in the course of exploratory calculations to see how sensitive *elemental* abundances were to the assumed physical conditions.

Our statistical program gives significance to the wavelength coincidences with Ni II lines in the spectrum of ι CrB, but not to those of Ni I: f(Ni I) = 1.0, f(Ni II) < 0.005. We therefore have some objective basis for rejecting the determination from Ni I, which gives a much less satisfactory fit, in figure 1 and ascribing the wavelength coincidences to chance. But even if a closer examination should show the higher Ni abundance to be more correct, we only have a conflict with *one specific prediction* of nucleosynthesis; we need not let one rotten apple spoil the barrel!

The fit for ϕ Her shown in figure 2 is also promising, with the exception of the point for scandium. This abundance is undoubtedly high, since the scandium lines are outstandingly strong in this star. The dynamic calculations (cf. Woosley, Arnett, and Clayton 1973) of nucleosynthesis show that scandium lies in a "bottleneck," which connects the flow of synthesis between two "clusters" of nuclides that tend to be in equilibrium among themselves. Its abundance is always very low, and consequently it could be easily increased by secondary processes which would hardly affect the relative positions of the more abundant elements.

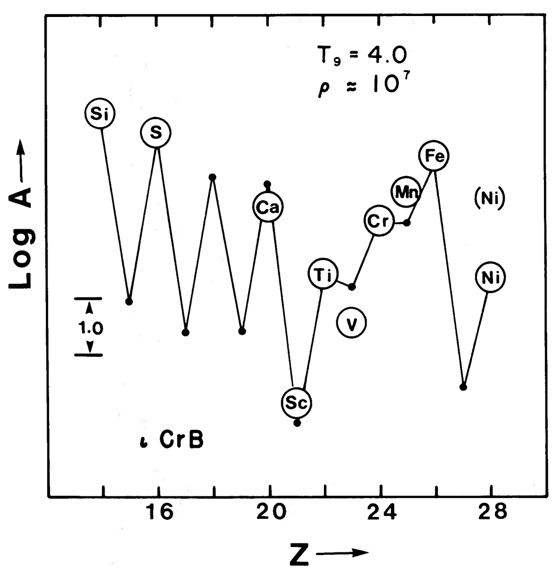

FIG. 1.—A comparison of quasi-equilibrium abundances with the determinations of Ross and Aller (1970). The stellar abundances are indicated by the chemical symbols inside the open circles. The filled circles connected by solid lines are the theoretical predictions. Logarithms of the proton and neutron densities are 27.787 and 19.815. The larger Ni abundance inside the parentheses is for Ni I. The lower point is for Ni II.

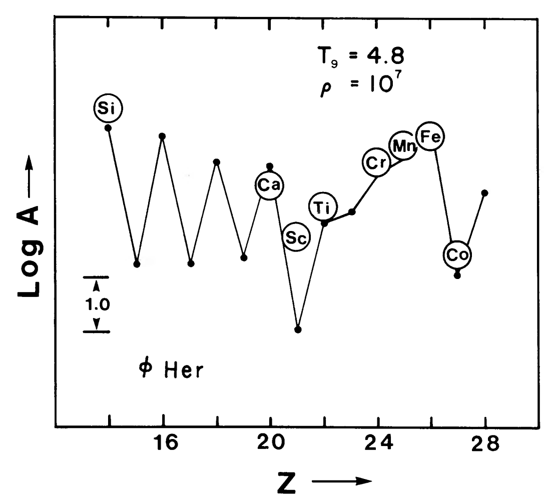

FIG. 2.—Same format as fig. 1. The stellar abundances are from Zimmerman *et al.* (1970). Logarithms of the proton and neutron densities are 28.704 and 22.875.

The three other manganese stars shown in table 2 show abundance patterns unlike any that we have obtained thus far. But we emphasize that we have by no means undertaken the complete multiparameter search that would enable us to say that *no* quasi-equilibrium fit could be obtained. It is also possible that the dynamic calculations of explosive silicon burning would be required.

Thus, it seems possible to say that the most formidable difficulties for nucleosynthesis are the deviations from the odd-even effect, rather than the peculiarities that occur near the iron peak.

V. SUMMARY

The manganese stars show three deviations from the odd-even effect that are in conflict with the predictions of nuclear astrophysics. We consider the yttrium anomaly to be the best indication of such a conflict. Consequently, it is a favorable problem for non-nuclear theories to attack. Michaud (1970) has made calculations that are highly promising for this particular case. We await their refinement.

We must remark, however, that manganese stars that are quite similar in effective temperature and surface gravities show different abundance patterns. Such differences inevitably call for an explanation in terms of a variety of processes with a variable relative mixture. Scientists may abhor theories with adjustable parameters, but nature may require them all the same.

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