# ARE THERE NORMAL UPPER MAIN SEQUENCE STARS: $\lambda$ BOOTIS, ...

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## Some Quotes from Cameron (1967)

> "... some 25 years ago when I analyzed Sirius ... the result was that there wasn't any difference between the sun and Sirius, but I am sure that this was because of a wrong temperature. If we had concluded that there was a difference, we would have been in trouble because the accepted dogma then was that all stars had the same composition and that all these effects were produced by special excitation mechanisms."–L. H. Aller p. 327.
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> O. J. EGGEN: The following remark is only partly facetious. Getting a "normal" star seems to be like getting 20/20 vision. I would think that this symposium, if nothing else, could decide to name at least two "normal" main-sequence A stars–or half-a-dozen would help.
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> W. P. BIDELMAN: I think that the I. A. U. should issue a standard list–which we could immediately start observing intensively and whittle down to nothing. p. 541

> Normal A stars are rather like normal people. If you don't look too hard, there seem to be quite a few of them. After you get to know them well, most seem a little crazy. CRC 1990.

**ABSTRACT**. Our concept of normal A stars is severely influenced by the dearth of features in the low resolution spectra of these objects that have been used for classification. The relatively small number of lines visible at survey dispersion has also led us to greatly simplify the complexity of spectroscopic patterns that can occur. The $\lambda$ Boo stars were noted as a class because of the prominence of the $\lambda$4481 line of Mg II. We call attention to lines of V II and Ni II that are strong in superficially normal stars, and surprisingly weak in strong-lined stars with obvious overabundances of chromium, manganese, and iron. It is also useful to note that iron itself can be both underabundant and overabundant in CP stars. We call attention to an important new work by Venn and Lambert that develops the earlier suggestion that $\lambda$ Boo stars may have formed from gas that has been separated from interstellar grains.

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# 1. INTRODUCTION

## 1.1.

Most of the problem of finding “normal A stars” is that we are not entirely clear about what one is. Sidney Wolff’s (1983) book on the A stars has an entire chapter on normal A-type stars, and being a careful worker, she starts with a clear definition: a normal A-type star is one that at classification dispersions shows none of the anomalies characteristic of the magnetic Ap, Am, $\lambda$ Boo, or other types of peculiar stars; that...appears to have a composition like the Sun’s; and that exhibits no variability, either regular or irregular.

This is a good definition, but I prefer not to use it here because it excludes too many stars. Most workers would agree that neither Sirius nor Vega would qualify as “normal” under this definition. We have known abundances in Sirius resembled those in Am stars since the 1960’s (cf. Conti 1970). Recently, the underabundances in Vega have refused to dissipate, and there has even been some indication of low level variability Fernie (1981).

My own preference has been to speak of *superficially normal stars*. This means those objects that can be classified under the MK *or* MKK system, that is, within a two-dimensional scheme, at roughly 125Å/mm. Thus, for the present purposes, all of the $C^2J^2$ (Cowley, *et al.* 1969) objects classified as late B or A dwarfs, without further qualification, are superficially normal. Both Sirius and Vega are superficially normal; $\lambda$ Bootis, arguably, is not (see below).

This working definition has the advantage of giving us some stars to talk about. On the other hand it has a distinct disadvantage, relative to Wolff’s definition. It limits peculiarities to those that can be recognized at low dispersion. Stars can qualify as being superficially normal if they have large *underabundances* of elements whose spectral lines cannot be seen at classification resolution. Actually, most elements can be underabundant. Near A0 V, at classification dispersion only lines of a very few elements are seen.

## 1.2.

Many critical elements are not examined in low resolution surveys–Sr, Y, Ba, etc. We know about the peculiar behavior of these elements in a few stars where abundances have been determined, or where high-resolution surveys have been made. But until recently, little has been done to study the star-to-star systematics of individual elements.

We know something about the systematics of scandium, yttrium, and zirconium in those calcium weak stars that are known as Am’s. Scandium is usually correlated with calcium Conti (1965), although the two do not vary in lockstep (Boyarchuk and Savanov 1986). There are stars with enhanced metals that have normal calcium and scandium, Conti's (1970) "type (c)." Dobrichev, Ryabchikova, and Raikova (1987) recently studied such a case, $\theta$ Vir. Moreover, there are scandium strong stars, e.g. 22 Com, $\phi$ Her. *Are they astrophysically less significant because they don't have a special name?*

There is a saying among those concerned with the treatment of disease, that progress with any particular form of illness is made only after the establishment of a "foundation" for that disease. Likewise, with anomalous stars, attention seems to be widely directed to *named* peculiarity types, such as mercury-manganese stars, or the Am's. With few exceptions (cf. Jaschek and Jaschek 1974) there has been surprisingly little attention devoted to variations within families and *why such variations occur.* My experience, asking theoreticians about the possible reason for variations within a peculiarity type, is that they start to talk about non-LTE.

One of the good things about the current interest in the superficially normal stars may be that, since they all have the same classification, people will take the definite abundance variations among them seriously.

We cannot overemphasize the importance of *selection effects* in the general question of normal *vs.* peculiar stars. There are huge differences in the low-dispersion spectra of late and early stars. The former are very "busy," the latter relatively "clean." This means that the detection of spectroscopic peculiarities is highly favored in early stars. It is well to note that the Am class exists because calcium deficiencies that are only a factor of three on the average, *can be seen* at low dispersion. Until the last decade or so, many *other* abundance anomalies of this order in lower main sequence objects were not taken seriously.

## 1.3.

The superficially normal stars may have a key role to play in our understanding of the chemically peculiar (CP) stars of the upper main sequence. Theories of chemical differentiation have provided us with the only self-consistent basis for an understanding of these objects. But the theories are rudimentary in the sense that they have only recently begun to make useful predictions of the behavior of spectral peculiarities as a function of the physical state and history of stellar envelopes.

Most interesting recent developments along this line have been those connected with the lithium abundance systematics in cluster giants and F dwarfs. Theory sets stringent limits on the otherwise unobservable hydrodynamics of stellar envelopes. These ideas are discussed by Charbonneau, Michaud, and Proffitt (1989), and Charbonneau and Michaud (1988).

In the simplest models of chemical separation, stars arrive on the main sequence with "normal" or "solar" abundances. The surficial abundances then change as a result of differential diffusion coupled with mass loss (cf. Vauclair and Vauclair 1982, Michaud 1986, Alecian 1986).

Thus far, any *history* of developing abundance *patterns* remains largely, though not entirely, unexplored. It is generally recognized that the helium must sink from the envelopes of Am stars *before* the calcium begins to settle. Since helium cannot be easily observed in the Am's, we can't look for stars with depleted helium but normal calcium and scandium, that is, nascent Am's. Differences in the anomalies of CP stars have generally been attributed to magnetic fields, mass loss, or turbulence, but *not* to any difference in the speed at which the anomalies develop. But some of the observed differences may be due to the relative maturity of the separation processes, and we just don't yet recognize which.

The superficially normal A stars can be important in this respect because they ought to be able to tell us something about the *order in which the peculiarities develop*. As a hypothetical (entirely) normal star begins to develop anomalies, it should at first show only mild peculiarities, and would still qualify as superficially normal. Consider the star 46 Aql, which Dworetsky (1975) has characterized at normal at dispersions above 10 Å/mm. At higher dispersion, the $\lambda$3984 line of Hg II is seen, along with other peculiarities (cf. Cowley 1980, Fig 2). The helium is weak, and manganese is not particularly strong, but P II is well developed, and, of course, mercury is weakly present. It is natural to ask whether the phosphorus and mercury anomalies are expected to develop *before* manganese. Modern time-dependent calculations of *abundance patterns* (cf. Alecian 1977) are urgently needed.

## 1.4.

We should not forget that among the well-known CP stars, there are some remarkable *underabundances*. Some thought must be devoted to the causes of these underabundances, and their possible relationship to the underabundances found in the $\lambda$ Boo stars. Let me pass the well-known deficiencies in the Am stars, and turn to some peculiarities that are less widely discussed.

The manganese stars 53 Tau (Adelman 1987, 1988a) and especially HR 562 (Ptitsyn and Ryabchikova 1986) are remarkable in their iron *deficiencies*. Ironically, 53 Tau has strong Mn II, but no Hg II $\lambda$3984. It is a manganese star, but not a mercury-manganese star. HR 562 shows the Hg II line clearly, as does HR 2844 (Allen 1977), another iron-weak manganese star. But we know that weak iron is *not* typical of manganese stars because some of them are undoubtedly iron rich, for example, HR 7664 (Allen 1977, Adelman 1988b) and 112 Her (Seligman and Aller 1970). Other manganese stars appear to have normal iron abundances.

The star HR 6000, whose peculiarities were noted by Bessell and Eggen (1972), has a silicon deficiency that is possibly two orders of magnitude (Andersen, Jaschek, and Cowley 1984). The silicon anomaly is enough to set this object off from typical mercury-manganese stars. Castelli, Cornachin, Hack, and Morossi (1984) report abundances generally in agreement with preliminary assessments of the above authors. In this star, lines of the CNO elements are arguably weak. HR 6000 is associated with the very young object HR 5999, and Castelli *et al.* suggest association with circumstellar matter. This may take on new significance in view of remarks to be made below in connection with the $\lambda$ Boo stars.

One of the most remarkable of the cool, Ap's is HR 8216 = HD 204411. The spectrum shows very strong lines from iron-group elements. The star was studied by Adelman in this thesis (cf. Adelman 1973ab), and Sargent, Strom, and Strom (1969) among others. In papers cited, abundances were determined for a few lanthanide rare earths. However, I don't think there is *any* evidence that the lanthanides are present in the spectrum of this star. Lines previously identified as due to lanthanides are more reasonably identified with iron group spectra, and in a number of important cases, with lines that Johansson and Cowley (1989) call *second generation*, that is, they are not in the Multiplet Tables.

The lanthanide to hydrogen abundance ratios in HR 8216 are arguably below solar. The *lanthanide to iron* ratios are indubitably sub solar, probably by more than an order of magnitude. It is interesting to compare the lanthanide spectra in superficially normal 95 Leo and HR 8216 (Cowley 1979, cf. Figs. 3b). We can clearly identify a number of lines in 95 Leo as due to lanthanides. We just cannot do this with HR 8216. This strong-lined, obvious CP star might be called superficially normal, or even metal weak, *if we were to look only at the elements heavier than barium.*

## 2. THE SUPERFICIALLY NORMAL STARS AND RELATED OBJECTS

Most of the spectroscopic work that I have done on CP stars has been with the 9682M coude spectroscope of the Dominion Astrophysical observatory (DAO). Since the dispersion is 2.4 Å/mm lines get pretty fuzzy-looking if $v\sin(i)$ is much greater than 10 km/sec. So from the beginning of the work in 1974, I looked not only for sharp lined CP spectra, but also for normal stars whose spectral lines were relatively sharp. More than 15 years ago, we noted (Cowley 1975) that the sharp-lined spectra of the early Am o Peg, resembled those of HR 6127 and $\eta$ Oph in having strong Ni II. Shortly thereafter we noticed that V II was also strong in these stars, and determined that vanadium was nearly an order of magnitude above solar in o Peg and HR 6127 (Cowley, Elste, and Urbanski 1978, cf. Fig 1).

We noticed the strength of the Ni II and V II lines in these superficially normal stars *relative to* those of a number of magnetic Ap's we had been surveying. What this means is that the following ratios are surely less than solar in *some* of the magnetic Ap's: V/Cr, V/Fe, Ni/Cr, and Ni/Fe. It is entirely possible that V/H and Ni/H are below the solar value, but that is much more difficult to prove in the rich and badly-blended spectra of magnetic Ap stars.

Not all traditional CP stars show this Ni II and V II weakness. Indeed, the well-known Am's such as 63 Tau or 32 Aqr or HR 178 (cf. van't Veer-Menneret, Coupry, and Burkhart 1985) have strong Ni II and V II. Similarities in the abundances of *those* superficially normal A's that are also known as hot Am's with the traditional Am's have been known since the work of the Stroms and Conti. What has not been very closely pursued is the relative weakness of Ni II and V II in some magnetic Ap's. We have published numerous illustrations of the phenomena described. In addition to the references cited, the reader might examine the behavior of the Ni II line $\lambda4362.10$ in the figures of Cowley (1979). The magnetic Ap star $\gamma$ Equ, which resembles Am's in a number of ways has strong V I and II, and only moderately enhanced lanthanides. The iron in $\gamma$ Equ is normal or possibly even a bit below solar.

The idea that there might be superficially normal A stars with *underabundances* has some history, part of which is reviewed by Cowley *et al.* (1982). We speculated that a rather large fraction of late B and A dwarfs might actually have modest (factors of 2 or 3) underabundances, similar to those found by Sadakane (1981) for 21 Peg and HR 7338. Since that time Holweger and his coworkers (Holweger, Steffen, and Gigas 1986, Holweger, Gigas and Steffan 1986, Lemke 1989, 1990) have studied a number of slowly-rotating A luminosity class III and V stars, and find a variety of abundance fluctuations. Most of these fluctuations are mild ($<$ 1 dex), but they defy simplistic description, and a responsible discussion degenerates into a tedious account of the behavior or individual elements in individual stars.

Among the iron-group elements, it would be useful to have more abundance information on vanadium and nickel, since these are the elements our qualitative surveys have shown to be the most variable. The oscillator strengths used for Ni II in recent work on "normal" A stars by Sadakane (1981, 1990) are arguably too large. The most recent Kurucz (1988) calculations for Ni II give $log(gf)$'s typically an order of magnitude smaller than those used by the abundance workers. Use of Kurucz's values would push the nickel abundances in the direction I feel is indicated by the comparative spectroscopy, but many of the transitions are LS-forbidden, and not expected to be accurate.

## 3. THE $\lambda$ BOOTIS STARS

Several papers on the $\lambda$ Boo stars note that the class consists of rather rapid rotators. Indeed, Hauck and Slettebak (1983) have suggested that the "moderately large" $vsin(i)$ can be used to distinguish the $\lambda$ Boo's from other peculiar stars with weak spectral lines. It is certainly true that $\lambda$ Boo itself, and those objects considered its congeners rotate much more rapidly than the typical Ap and Am stars. However, we now know of quite a number of late B and A stars with weak lines, and it is reasonable to ask if their $vsin(i)$'s are different from those of the $\lambda$ Boo stars for any reason *other* than selection.

Suppose the $\lambda$ Boo chemical peculiarities were to occur generally in stars with $vsin(i)$ distributions typical of early A stars. It would then be *natural* if the first few such stars found had rotational velocities that were typical of the type, that is, moderately large. But even if rapid rotation were a necessary condition for the $\lambda$ Boo phenomenon, there ought to be a few members of the class with sharp lines just because of projection. Are Vega, and the Sadakane stars 21 Peg and HR 7338 such objects? The weak-metal star 50 Lib (HR 5959) studied by Lemke (1989, 1990) is another candidate. It has a $vsin(i)$ of 34 km/sec. Its colors (Hauck and Mermillod 1980, Rufener 1980) certainly place it among the Hauck-Slettebak $\lambda$ Boo stars.

Baschek and Searle (1969) in one of the classical studies of $\lambda$ Boo stars pared down the rather small number of objects then known to three, on the basis of the oxygen abundances. These were "normal" in the chosen three. Whether this distinction was useful remains to be seen. It is now well established that the abundances of certain elements may vary enormously within what is widely accepted as a peculiarity class.

If we accept the stars of Hauck and Slettebak's (1983) Table 1 as a working set of "official" $\lambda$ Boo's, we find a most remarkable thing both in the $vsin(i)$'s and the space motions of this specific set. The 8 $vsin(i)$'s are tightly clustered about a mean of 101 km/sec. We have devised some interesting games to see at what confidence level we could reject the null hypothesis that these $vsin(i)$'s were drawn at random from some (uninteresting) background populations of late B and A stars.

Without doing any fancy calculations at all, one might guess that there was nothing unusual about the mean $vsin(i)$ of the Hauck-Slettebak stars. We find, for example, for 1081 B8 - A7, V and VI's from the Bright Star Catalogue, a mean of $vsin(i)$ is 125 km/sec, and a standard deviation of 82 km/sec. This sample included binaries. On the other hand, the standard deviation of the $vsin(i)$'s of the Hauck-Slettebak stars was quite unusual. It was only 14 km/sec, and did not occur in any of several thousand Monte Carlo trials that we made by chosing random samples of 8 from the pool of 1081 values of $vsin(i)$. I suspect that the small standard deviation may be at least partially explained by selection effects, suggested below. We shall therefore not present the details of the various tests here.

Morgan (cf. Morgan 1983) first noted $\lambda$ Boo on 30 Å/mm Yerkes radial velocity plates. This is very close to the dispersion used in Slettebak's (1954) classic study. While Morgan points out that "the characteristics show up at 120 Å/mm," Houk (1990) has concluded that the stars cannot be consistently detected in her revised HD classification. There are two points to be made here. First, the $\lambda$ Boo stars may be called "almost" superficially normal, since they are not easy to detect at classification dispersion. Second, the relatively high spectral resolution used in the surveys that picked up additional $\lambda$ Boo stars probably influenced the domain of $v sin(i)$ in which they were noticed.

At 20 Å/mm lines start to "sharpen up" as $v sin(i)$ approaches the limiting resolution–roughly, 20 km/sec. Since sharp lines tend to appear stronger than broad ones, it is at least possible that slow rotators with weak $\lambda$4481 were less conspicuous than their broader-lined congeners. On the other hand, 130 km/sec is already some 6 times the resolution of Slettebak's survey, and intrinsic weakness of the $\lambda$4481 line was perhaps less noticeable.

We looked at two other sets of (heterogeneous?) objects, those of Baschek and Slettebak (1988), which includes "suspected" $\lambda$ Boo's , and Abt (1983), who calls his objects "Weak $\lambda$4481 Mg II stars." Both of these sets show expected means and small standard deviations of the $v sin(i)$ distributions. But the latter $\sigma$'s are some three to four times larger than those of the Hauck-Slettebak list, and would occur once in some 10 or 20 random samples of uninteresting stars. They are not *highly* unusual. Interestingly, some $\lambda$ Boo candidates were found by Mustel, *et al.* (1958) using a dispersion of 72 Å/mm. We have not studied them separately.

The space motions of Hauck and Slettebak's (1983) stars are unusual. Like the standard deviation of the $v sin(i)$'s, they are not expected. Almost all of the U, V, and W-values are negative! This grouping certainly did not arise by chance sampling of the normal A-star population (cf. Eggen 1984). Still, it might happen for some uninteresting reason. We can only remark that the space motions deserve further consideration.

A important preprint by Venn and Lambert (1990) develops an old suggestion that the metal-poor A stars might be explained by the separation of interstellar grains and gas. The idea was published, for example, by Cowley, *et al.*(1982), who also suggested that Vega and other metal-poor stars with low $v sin(i)$'s might simply be more slowly rotating counterparts of the $\lambda$ Boo's. The general notion of explaining depletions in terms of refractory condensates is also found in the work of Drobyshevski, who has written voluminously on related topics (cf. Drobyshevski 1986), and perhaps elsewhere.

But Venn and Lambert have developed these ideas in a most interesting way, on the basis of their new abundance analyses of "the" uniform sample of three stars, $\pi^1$ Ori, 29 Cyg, and $\lambda$ Boo itself. They suggest, following the work of Sadakane and Nishida (1986) that the infrared excesses of $\lambda$ Boo and Vega are indications of the residual grains that belong to the depleted gas from which the stars formed.

An important part of the Venn-Lambert hypothesis is the result that the CNO elements are nearly normal, both in the interstellar medium, and the three $\lambda$ Boo stars analyzed by them plus Vega. On the other hand, Adelman and Gulliver (1990) find helium to be depleted in Vega by about a factor of three, and there is no indication of such helium depletions in the interstellar gas. We have known since the work of Kodaira (1967), and Baschek and Searle (1969), that some iron-poor, superficially normal stars have depletions of one or more CNO elements. Perhaps these depletions happened as a result of stellar diffusion.

If the $\lambda$ Boo stars are formed from grain-depleted interstellar gas, we might expect the stellar abundance patterns to resemble those of the interstellar gas. Venn and Lambert do not find this for their stars, but they have an entirely plausible explanation. The depleted gas has contains a mixture of material with normal composition. Because the iron group (Ca - Ni) depletions of the interstellar gas are are very large–factors of up to $10^4$–we may to a first approximation, neglect entirely the metal content of this depleted gas, and consider it simply a dilutor. Then all of the iron-group elements would be depleted by similar factors, as is observed.

We draw attention to an important cosmochemical principle, that if chemical fractionations appear in one place, *complementary patterns* should appear somewhere else. Some stars may contain more than the cosmic complement of refractory elements. There could also be stars whose surface abundances should reflect the depletion of refractories, that is, where the Venn-Lambert dilution mechanism is not active. Finally, we need to know the how stellar diffusion will modify all of these patterns.

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