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THE METALLIC-LINE STARS*†

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I. Introduction

Metallic-line (Am) stars, first described by Titus and Morgan (1940), are stars showing a particular *spectroscopic* anomaly. This anomaly was defined on the MK system by Roman, Morgan, and Eggen (1948) when they listed 13 stars that showed a diverse spectral classification. The ionized Ca (Ca II) line at λ 3933 (K) showed an early A spectral type while other metallic lines were late A or F. The hydrogen lines were intermediate. It was subsequently found that this spectroscopic anomaly was fairly common among A stars (Slettebak 1949).

The recently published compilation of MK spectral types among the bright A stars by Cowley et al. (1969) lists about eleven percent of them as Am. This number must be a lower limit because (1) part of the A star sample includes giant stars; (2) some Am stars are slightly too late to be in the catalog; and (3) others are not readily recognizable at MK dispersion (see §II). Attempts have been made to explain the Am stars but without noted success. The time is ripe for an appraisal of the observational and theoretical situation as it exists today because there have been important advances since the last reviews related to this topic (Sargent 1964; Böhm-Vitense 1960).

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The problem of the Am stars should be thought of as a *phenomenological* one; a point of view which was also expressed very clearly by Thomas (1969) in another context. We should be concerned with explaining the Am *phenomenon* rather than the Am *stars*. Stars that show the Am phenomenon are to be considered Am stars by definition. The definition I wish to adopt is more physical in description than the MK criterion. My review is intended to justify the following definition:

> The Am phenomenon is present in stars that have an apparent surface underabundance of Ca (and/or Sc) and/or an apparent overabundance of the Fe group and heavier elements.

This is to say that, when an atomospheric analysis is considered, anomalous deficiencies or excesses of these elements appear. These anomalies are considered real if they are larger, say, than a factor of two and persist regardless of whether the analysis is a "coarse" analysis or a "fine" one utilizing sophisticated methods, within the framework of local thermodynamic equilibrium (LTE).

If non-LTE effects, as yet unspecified, are important, the derived abundances may be only "apparent" and not indicative of the amount of each element present on the stellar surface. These spectroscopic anomalies are apparent at MK dispersion for many stars while only detailed spectroscopy reveals them for other stars. However, the phenomenon must be similar in both.

Implicit in this definition, and in the MK one, is the existence of three subgroups of Am stars. Compared to normal A stars, these are: (a) stars with weak Ca (Sc) *and* strong metallic lines; (b) stars with *only* weak Ca (Sc) lines; and (c) stars with *only* strong metallic lines (but not strong Ca (Sc)). Examples of each subclass, using MK classification, are: (a) 63 Tauri (Roman et al. 1948); (b) α Geminorum B (Roman et al. 1948); and (c) 17 Hydrae (Slettebak 1963). Common to all Am stars is a difference between the Ca (Sc) and other metallic lines. The "metallic-line" star, HR 5317, discussed by Kondo and McClusky (1969) is not Am by this definition because Ca and Sc are enhanced along with other metals. One important distinction between the Am stars and super metal-rich stars (Spinrad and Taylor 1969) is that the latter have strong Ca and Sc along with other metallic lines.

My definition describes an observable facet of the Am phenomenon. Other criteria, such as duplicity, high microturbulence, and low effective gravity, have sometimes been used to define Am stars. The relevance of these secondary criteria will be discussed further on.

II. Physical Characteristics

A. *Region of the HR Diagram*

The Am stars defined by Roman et al. (1948) are in the (hydrogen) spectral-type range A4 to F0. Subsequent studies (Baschek and Oke 1965) showed that this classification was roughly consistent with derived effective temperatures. Further classifications with the MK system (Slettebak 1949, 1955; Cowley et al. 1969) have also placed Am stars in this spectral range. It is apparent from lists of this kind that the latest-known Am stars are at about type F0. τ Ursae Majoris is usually considered the prototype of a late-type Am star.

Preston (1961) discussed the F star HD 174704, whose spectrum appeared to be peculiar according to Bidelman (1957) and which, after high dispersion analysis, turned out to be Am. It was not an obvious Am star at low dispersion because the Ca II K line was not particularly weak. The analysis showed this star to be similar to τ UMa but less deficient in Ca and more deficient in Sc. Preston suggested that other relatively late Am stars which also had these characteristics might be found at high dispersion. HD 174704 is hotter than τ UMa (Sargent 1964).

The rather abrupt cutoff of late Am stars at spectral type F0 must have important physical meaning. This boundary is near to, but does *not* coincide with, the onset of an extensive hydrogen subsurface convection zone. This occurs in stars of spectral type F4 and cooler, according to observations of stellar H and K emission (Wilson 1966), stellar rotational braking (Kraft 1967), and theory (Demarque and Roeder 1967).

Conti (1965*b*) discussed the discovery of Am stars earlier than A4. In early A spectral type, as is well known, there is a difficulty in classification due to the hydrogen lines being at a broad maximum of strength. Since in this spectral range the temperature of a star is not determinable from line spectra alone, a star in which the metallic lines are strong compared to the effective temperature will not be recognized. The K line is nearly on the flat part of the curve of growth, and moderate changes in the Ca II present will not be derivable from the line strength.

Sirius and 68 Tau are well-known A stars, classified as normal on the MK system. Sirius (Kohl 1964) and 68 Tau (Conti, Wallerstein, and Wing 1965) were found to have Am abundance characteristics when a detailed model atmosphere analysis was performed. These stars show the Am phenomenon and hence may be considered to be Am stars.

Conti (1965*b*) showed that other early A stars having Am abundance characteristics could be identified by another spectroscopic method. This method involved a ratio between a Sc II line and a Sr II line, both of which behave differently in Am stars than in normal stars. A number of early Am stars were found with this spectroscopic criterion. Several of these stars were subsequently shown to be Am by means of a high-dispersion model atmosphere analysis (Conti and Strom 1968*a,b*). I will retain the terminology "early" Am stars for these stars because of a distinction between them and the later types (see §II *C*). Phenomenologically, however the two Am types are identical.

Am stars are found in well-studied clusters such as the Hyades and Coma. Their position in the HR diagram in these and other clusters puts them on or near the main sequence. From other sources of absolute magnitude (see §II; Jaschek and Jaschek 1959) there is also evidence that Am stars are main-sequence stars. There are no known giant stars that show Am characteristics. Stars later than F0 on the main sequence, and giant stars, have an extensive surface convection zone. The absence of Am stars among these types suggests that the Am phenomenon and a deep convection zone are mutually exclusive.

B. Membership in Clusters

A survey of those Am stars known to be in clusters was given by Jaschek and Jaschek (1967). They concluded that the Am phenomenon was only found in "middle-aged" clusters such as the Hyades and Coma. The conclusion that Am stars were not found in young clusters, however, rested mainly upon the fact that none were known in the Pleiades. It was later found (Conti 1967; Conti and Strom 1968*a*) that several (early) Am stars do indeed exist in this cluster.

Conti and van den Heuvel (1970) concluded that the statistics of the search for Am stars in young clusters was insufficient. It is necessary to investigate the *late* A stars in a young cluster spectroscopically. With an Am expectation of 10–20 percent, at least 50 late A stars must be investigated before it is possible to draw a firm conclusion about a deficiency of Am stars. Conti and van den Heuvel (1970) found two Am stars in M7, which contains a B6 star and several B9 stars. However, this evidence is not completely conclusive and further spectral classification studies are planned. It seems well within the realm of possibility that Am stars are "born" abnormal or become so very shortly after reaching the main sequence.

Pesch (1967) has called attention to two A stars in the old cluster M67 that show the spectral characteristics of Am stars (our subclass (a)). Sargent (1968) confirmed their Am appearance (as our subclass (c)) however, and interpreted these stars as horizontal-branch stars with about one solar mass. If this interpretation is correct, then the Am phenomenon can occur in evolved stars of one solar mass. The Am phenomenon would then be related to an "instability" region of the HR diagram (rather like the cepheid gap). Other clusters the age of M67 and containing horizontal-branch stars have not been well studied spectroscopically.

Proper motion studies have been used to determine the age of Am stars (Jaschek and Jaschek 1967). One may conclude that Am stars as a group are neither a very young population nor a very old population. Such studies do not eliminate the possibility that *some* Am stars are very young or very old. Schlesinger (1966) has shown that the space motion of Am stars is indistinguishable from normal stars.

C. *Rotational Velocity*

Slettebak (1955) pointed out that the stars classified spectroscopically as Am stars showed lower measured rotational velocities, $V \sin i$, than normal A stars in the same spectral range. The normal A stars had $V \sin i = 150$ km/sec, whereas the Am stars had $V \sin i = 55$ km/sec. This relation persists in all types of Am stars studied (Abt 1965; Conti 1965*b*; Milton and Conti 1969) and must represent a fundamental physical parameter.

Abt (1961) demonstrated that Am stars are not necessarily seen "pole-on" and that the sin i in the observed rotational velocity does not dominate the distribution, hence the Am stars have small V. A very important question is whether this low rotational velocity is a *cause* or a *result* of the Am phenomenon.

The broadest-lined known Am star is μ Aurigae, for which $V \sin i = 90$ km/sec (Slettebak 1955). According to Morgan (Abt 1963) there should be no difficulty in recognizing rapidly rotating Am stars if such stars exist. Deutsch (1967) has argued that the statistics of $V \sin i$ for Am and A stars are consistent with the statement that $V < 100$ km/sec is a *necessary* and *sufficient* condition that a star be Am. From the statistics of rotational velocities among the late A stars, we can conclude that all slow rotators are Am stars and that no normal late A star is a slow rotator. The very few late A stars with sharp lines are presumed to have small sin i.

Conti (1965*b*), Deutsch (1967), and van den Heuvel (1968*a,b*) have discussed the statistics of rotation among early A stars and showed that at this spectral type there was an "excess" of slow rotators. An unsettled question among these writers was whether or not the "excess" slow rotators are Am stars or evolved "horizontal-branch" stars (or both!). If the Am stars are not the "excess," then they are on the "tail" of the distribution of rotational velocities. In any case, there are some early A stars that are slowly rotating but are not Am stars. Hence, among early A stars slow rotation is a necessary condition for an Am star but it is not a sufficient condition. This is the only distinction between early and late Am stars.

D. Membership in Spectroscopic Binary Systems

In two important papers, Abt (1961, 1965) discussed the problem of duplicity among Am and normal A stars. In the first paper, out of a sample of 25 bright Am systems, 22 were found to be binaries. The other three stars *could* be considered to be pole-on systems (although the statisitics are also such that one or more of these might not be binaries either). Some, but not all, of the Am systems had short periods ($P < 100$ days). In the second paper, out of 55 bright normal A stars studied, 17 were found to be binaries, but all had periods longer than 100 days. The fraction of long-period binaries among Am stars and normal stars is similar, according to Abt.

Abt (1965) showed that the distribution of periods of Am stars was bimodal with the long-period "hump" matching the distribution of normal A stars. Van den Heuvel (1970) showed this hump to be artificial due to Abt's use of a log *P*, number distribution. This hump practically disappears when a log *P*, log number distribution is used. The distribution of Am stars is not bimodal but is single valued and matches the normal A stars at the long-period end. The existence of a bimodal distribution would have suggested a different origin for the short-period Am stars.

Recently, Abt and Bidelman (1969) have classified the spectra of some late A stars that were known short-period binaries. All binaries with periods greater than 2.5 days were found to be Am. Several binaries with periods less than 2.5 days are not Am. These results lead to the conclusion that in the late A spectral-type range, duplicity and the Am phenomenon are somehow related. It would appear that this relationship is indirect. Abt (1967) has suggested that the slow rotation is the physical characteristic that is important. He suggests that the short-period Am binaries are slowed by tidal interaction to synchronous rotation and thereby become Am. Some binaries with periods less than 2.5 days rotate too rapidly to be Am.

Conti (1968*a*) pointed out that the fraction of short-period binaries was roughly constant along the main sequence from B to G, if the Am stars were counted. If the Am stars were not counted, then there was a conspicuous gap in the distribution of binaries in the late A star range. This strongly suggested that Am binaries are unevolved much as the binaries of other spectral type are presumed to be. If some Am binaries are unevolved, then the Am phenomenon cannot be a direct consequence of some evolutionary stage.

The separation of the long-period Am binaries suggests further that there is no physical interaction at the present time in Am systems and that duplicity itself is not a direct cause of the Am phenomenon. The long-period Am systems are the slow-rotator portion of the distribution of all long-period binaries. The existence of a few single Am stars (Conti 1969*a*) is then not surprising. Conversely, duplicity cannot be considered a test for deciding whether or not a star is Am. What apparently is crucial in the late A-type stars is that a short-period binary has a slow rotation due to synchronism which in some yet unspecified manner leads to the Am phenomenon. Other slow rotators in this regime also are Am.

Among the early Am stars, some are known binaries of short period (Conti 1965*b*, 1968*b*). All the short-period early A binaries with slow rotation investigated by Olsen (1969) were found to be Am. However, at least three early A short-period binaries (95 Leonis, HD 2421, and 7 Camelopardalis), with small $V \sin i$, are not Am.

E. Membership in Visual Binary Systems

Slettebak (1963) made an extensive classification study of visual binary pairs. Nine Am stars could be given absolute magnitudes from the spectral types of their companions; these were consistent with their being main-sequence stars. Slettebak suggested that Am stars could not be very young as no Am stars had B companions. However, there was only one combination of a B star with a late A star in Slettebak's list, and in this case, π Bootis, the primary is a peculiar A (Ap) star and the secondary, in Slettebak's words "could be an Am star." A more recent study of visual binary systems containing B stars has been made by Murphy (1969). No Am stars were found but only seven late A stars occur as secondaries. With a ten-percent expectation of Am stars, the statistics from both studies are inconclusive as to questions of youth among Am stars (see §II *B*).

One visual binary is known (Slettebak 1963) in which an Am primary is found with an evolved F subgiant (see also discussion after Jaschek and Jaschek 1967; Cowley et al. 1967). This system (ADS 8690) *could* contain a horizontal branch Am star, a visual binary analogue of the M67 cluster.

Several visual binaries contain both components as Am stars (e.g., ν Draconis). There seems to be some correlation between the brightness differences and the differences between the K and metallic-line types but, according to Slettebak (1963), these results are inconclusive. In those visual binaries containing an Am primary and a normal secondary, the secondary is either later than F0 or rotating rapidly. In the three visual binaries in Slettebak's list with an Am secondary and a normal A primary, the primary is an early Am star (Conti 1965*b* and unpublished).

F. Membership in Eclipsing Binary Systems

Several Am stars are known which are eclipsing binaries, e.g., RR Lyncis and WW Aur. Photoelectric studies of these systems have shown that they are "detached" with no particular abnormalities in the light. Spectroscopic studies have indicated normal masses for the components (Popper 1959, 1962). Olsen (1969) has shown that, for a number of eclipsing Am systems, the gravities are normal. These arguments are independent of the atmospheric analysis (see §IV).

Semidetached eclipsing binaries are thought to be in an advanced evolutionary stage. There is no evidence that any semidetached binaries are Am.

G. Miscellaneous Physical Characteristics

Six Am stars were reported to have a magnetic field of the order of a few hundred gauss (Babcock 1958). Eight other Am stars had no detectable field. The evidence was based on a few spectrograms per star, at most. However, Conti (1969*a*) with 15 spectrograms was unable to confirm a field in 16 Orionis. This Am star was reported by Babcock to have a field of reversing polarity. Another Am star studied by Conti also gave no evidence of a field of more than a few hundred gauss. Magnetic fields in Am stars are small, or nonexistent, in contrast to the Ap stars where fields of several thousand gauss are often found (Babcock 1958).

A class of variable stars called the δ Scuti stars has often been considered to be related to the Am stars (e.g., Eggen 1963). The δ Sct stars are found in the same region of the HR diagram and often show, spectroscopically, enhanced metallic lines. A detailed analysis of the δ Sct star δ Delphini, using model atmospheres (Reimers 1969), showed that Ca and Sc were not particularly underabundant, nor was the Fe group particularly overabundant. On the other hand, an analysis of this same star (and two others) by Bessell (1969), using a curve-of-growth method, has also been published. Bessell concluded that all three stars were Am. It is not clear why divergent conclusions have been reached by the two writers for the same star. However, the quoted abundances are not very dissimilar. These stars are not clearly proven to be Am.

A very detailed photometric survey of variability has been made in the A–F region of the HR diagram by Breger (1969). Many previously unidentified δ Sct variables were found. However, only one star was found which had previously been classified as Am. This star, HR 114, turns out to be a normal F2 V star on subsequent high-dispersion spectral classification (Milton and Conti unpublished). Seven other Am stars studied by Breger were not variable. This result is very interesting because the instability gap delineated by the δ Sct stars cuts the main sequence between F2 and A4, according to Breger (1969). It would seem, therefore, that the Am phenomenon and the δ Sct phenomenon may be mutually exclusive.

III. Photometric Indices

UBV color indices of stars classified as Am show them to have $(B-V)$ color indices roughly corresponding to the hydrogen spectral type (Jaschek and Jaschek 1957, 1959). The $(U-B)$ color indices are often too faint, which suggests either a difference in the Balmer jump (hence the gravity) or in excessive ultraviolet line blanketing. Since giant stars fall in the same region of the $(B-V)$, $(U-B)$ diagram, *UBV* color indices *alone* cannot be used to detect Am stars.

Baschek and Oke (1965) showed that the $(U-B)$ deficiency in Am stars was due to line blanketing alone by comparing the observed color indices with those from adopted model atmospheres. Ferrer, Jaschek, and Jaschek (1970) have confirmed this result by using the infrared color indices of Am stars to derive the deblanketing trajectories. These writers showed that the deblanketing necessary to bring the Am stars to the normal $(B-V)$, $(U-B)$ relation was proportional to the spectroscopic "metallicity." The metallicity is the difference between the hydrogen and metallic spectral types. Slight differences between the temperatures derived from the observed $(B-V)$ color indices and the hydrogen line profiles in Am stars are presumably due to small excess line blanketing in the color indices.

Strittmatter and Sargent (1966), following the results of Baschek and Oke (1965), deblanketed Am stars in several galactic clusters. They showed that the Am stars were closer to the zero-age main sequence than the other cluster stars. They interpreted this effect as due to the low intrinsic rotation of Am stars. The other cluster stars having appreciable rotation are displaced to the red in a color, magnitude diagram, as predicted by theory.

On the Strömgren (1963) m_1, $(b-y)$ color system, Am stars often have large m_1 indices, compared to normal stars of the same $(b-y)$ index. The m_1 index is a direct measure of the average metallic line strength in the violet. A related index $[m_1]$ (Strömgrem 1966) is reddening and gravity independent. The increased metallic line strength could be due to an abundance effect or to microturbulence. We will see in section IV that the latter effect is less important for Am stars.

Several well-known Am stars do not have a peculiar m_1 index. Conti and Deutsch (1966) suggested that this could be due to the presence of a companion star, diluting the excessive m_1 to a more normal value. At least one "low"-m_1 Am star, 15 Vulpeculae, does not appear to be a binary (Conti 1969*a*). It appears that Am stars with normal m_1 belong to our subgroup (b). Because some Am stars do not have a large m_1 index, a photometric study using Strömgren indices alone will not find all of the Am stars. Milton and Conti (1969) showed that if m_1 was greater than 0.230 for a late A star, the star was spectroscopically an Am star. This criterion isolates about half of the Am stars. Strömgren (1966) has stated that if the $[m_1]$ index differs by at least 0.035 from normal this is a photometrically sufficient condition for a star to be Am.

Henry (1969) has devised a k index which measures the strength of the K line. This index, used in combination with the $(b\text{-}y)$ or Hβ color index is often anomalous for Am stars. However, some Am stars do not have a peculiar k index. These are presumably in our subgroup (c).

Figure 1, adapted from Henry (1969), shows a diagram of Δk with $\Delta[m_1]$, the deviation of each index from the normal star relation. This diagram contains Am stars showing both Δk and $\Delta[m_1]$ deviant, and stars showing *only* Δk or $\Delta[m_1]$ deviant. This material supports the occurrence of three subclasses of Am stars as is suggested by the spectral classification. The occurrence of Am stars with differing deficiencies and excesses of elements suggests that two processes are involved in the Am phenomenon, one process tending to make Ca (Sc) deficient, the other leading to the excesses of the other elements.

Henry points out that his Δk, $\Delta[m_1]$ diagram clearly separates the Am stars from the normal stars. (Even 15 Vul, at -0.17, -0.15, is separated.) This suggests a distinct cause for the Am phenomena. This very important result should be checked by k-index photometry of additional stars.

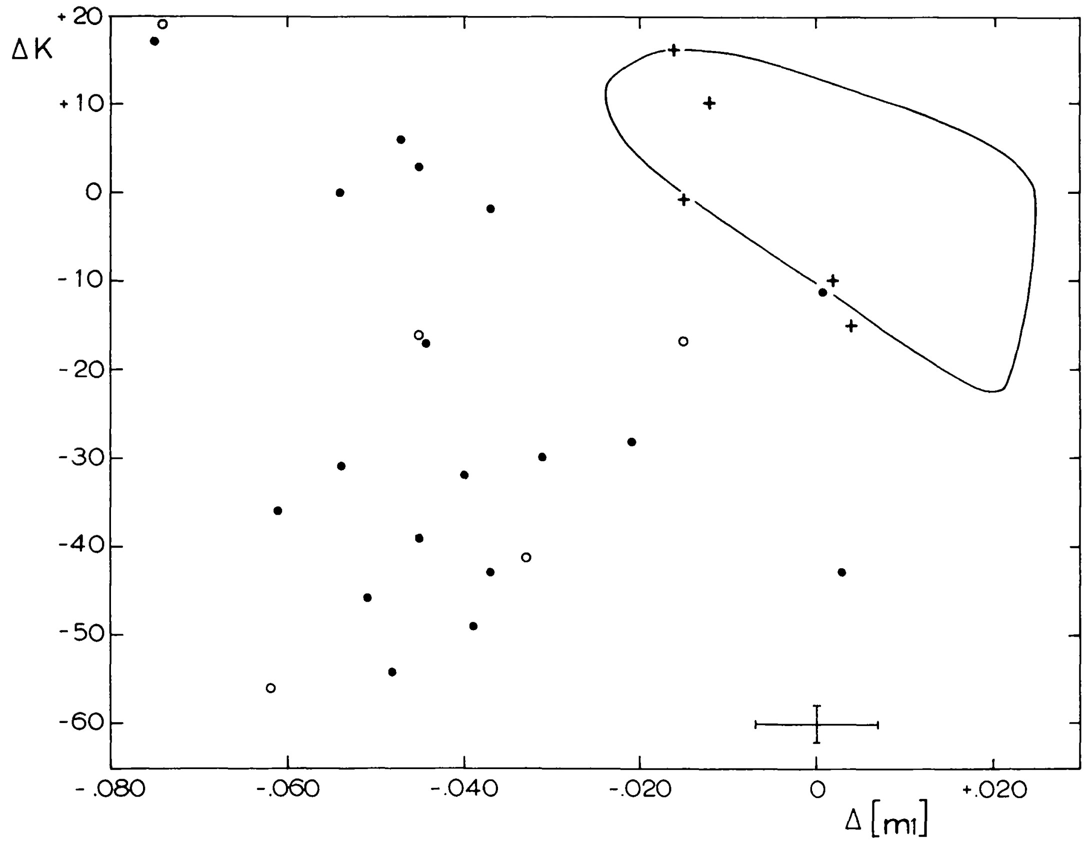

FIG. 1 — Comparison of Δk and $\Delta[m_1]$ indices (adapted from Henry (1969). The open circles are the stars of Table I; the filled circles, other Am stars. The crosses are stars listed as Am by Henry but *not* classified so in the compilation by Cowley et al. (1969). The area enclosed by the solid line contains the normal A stars according to Henry. There is a clear separation between normal and Am stars using these two indices.

Three stars have been listed in the literature cited by Henry as Am but are not deviant in Figure 1. Two of these are normal in the more recent spectroscopic classification of Cowley et al. (1969), but 60 Leo remains classified as Am. Three other stars with nearly normal indices were cited by Henry as "perhaps Am." Two of these were normal according to Cowley et al. (1969) and 47 Herculis was considered "metals only slightly enhanced."

Both the spectral classifications and the photometry of Henry are remarkably consistent in defining Am stars. Henry's Δk, $\Delta[m_1]$ method is the first photometric method devised which finds *all* and *only* the Am stars. Further work using this system is very desirable as photometry can be more precise, in principle, than spectroscopic eye estimation.

IV. Atmospheric Analysis

Here we are concerned with the atmospheres of the Am stars; consideration of abundances is deferred to the next section. The classic study of F stars, including the Am star τ UMa, was carried out by Greenstein (1948). Greenstein derived atmospheric parameters for several F stars and τ UMa using equivalent widths and the curve-of-growth method. The excitation temperature and an ionization equilibrium of V, Cr, and Fe indicated a low effective gravity for the Am star. A high "microturbulence" was derived from the shape of the curve of growth. (For the present discussion I will consider the microturbulence as merely a parameter derived from a curve of growth, or a more sophisticated study. Its physical significance is not fully understood.)

Greenstein (1948) concluded that the atmosphere of τ UMa was anomalous since it was like the atmosphere of the supergiant α Persei although the star itself had the luminosity of a dwarf. Since Greenstein's work, some investigators of Am stars have concluded that low gravity (and low electron pressure) are important features of Am stars (e.g., Böhm-Vitense 1960). I think this conclusion may be unwarranted in the light of new results.

The conclusion that τ UMa had a low effective gravity was almost certainly reached because Greenstein used too low an ionization temperature. At that time, Am stars were thought to be F stars and τ UMa was analyzed relative to stars of spectral type about F5. The hydrogen lines and (deblanketed) color indices of τ UMa suggest it is about type F0 (Baschek and Oke 1965). A higher effective temperature for τ UMa would mean that a higher gravity would be derived. (This can be readily visualized by referring to Figures 15 and 16 of Conti 1965*a*—see also Hack 1966.) A reanalysis of τ UMa using model atmosphere techniques would be useful.

Two other Am stars were analyzed by Micziaka et al. (1956) by a method similar to that used by Greenstein (1948). Both these stars also showed "high" microturbulence and low effective gravity. Preston (1961) found similar results for HD 174704. The conclusion about the low effective gravity in these stars suffers the same criticisms as that for the τ UMa analysis (see also Sargent 1964).

Subsequent studies of Am stars have utilized model atmospheres and the assumption of LTE. Conti (1965*a*) analyzed five Am stars in the Hyades. There was evidence for a marginally low effective gravity and electron pressure in only two of the stars. Van't Veer-Menneret (1963) had analyzed one of these Hyades stars (63 Tau) with a more sophisticated model atmosphere technique and had found essentially a normal gravity. Provost and van't Veer-Menneret (1969) have found a normal effective gravity for another Am star, 22 Serpentis. Similar results for other Am stars were found by Praderie (1967*a*).

Smith (1970) has analyzed a large number of Am stars in clusters and in the field. He finds normal dwarf effective gravities for all his Am stars. It is most probable that a low electron pressure is not characteristic of the Am phenomenon but was the mistaken result of using too low an effective temperature in the first few investigations.

All these investigators have found a "high" microturbulence for the Am stars. By high it is meant that about 4–6 km/sec of microturbulence is needed to fit all lines on a curve of growth. The numerical value of this parameter is higher than that needed for normal F stars or normal (early) A stars.

Conti and Strom (1968*a*) have found high microturbulence for four normal late A stars in the Pleiades. Baschek and Reimers (1969) have pointed out that these and other observations suggest that high microturbulence is a common feature of the *normal* late A stars and that Am stars are not anomalous in this regard. These observations have been confirmed by Chaffee (1970) who studied the change of the microturbulence parameter along the main sequence. He found a high microturbulence in normal stars just in the late A range. It seems most likely that the parameter of microturbulence is not peculiar to Am stars but is shared by all stars in that region of the HR diagram. Hence microturbulence is not important for the Am phenomenon and a high value of microturbulence therefore is not a necessary criterion for an Am star. If Am stars are not abnormal in their microturbulence when compared to stars of similar temperature, then differences in photometric indices such as $\delta(U-B)$ and $\Delta[m_1]$ are primarily measures of abundance. We anticipate that the Am stars will show anomalous abundances for common elements (see §V).

The early Am stars do not have a particularly high microturbulence (Conti and Strom 1968*b*). We can now understand that this is because they are of the early A type.

Although no detailed line-profile observations of metallic lines in Am stars have yet been made, there is no evidence for any anomalies (Greenstein 1948). There is no evidence of emission lines or of dilution effects (Greenstein 1949). The hydrogen line profiles (Baschek and Oke 1965; Conti 1965*a*) do not appear to be abnormal. There is no evidence for spectrum variation. So far as any atmospheric anomalies are concerned, they appear *exclusively* in the derived abundances of elements.

V. Abundance Analyses

All analyses of Am stars have used equivalent widths and are based on the hypothesis of LTE. The first star for which results were derived was τ UMa (Greenstein 1948, 1949). Ca and Sc were found to be deficient, and several other elements were found overabundant. The Fe peak elements were normal. Similar results were obtained by Micziaka et al. (1956) for 8 Comae Berenices and 15 Vul and by Preston (1961) for HD 174704. These studies used a relative curve-of-growth analysis and determined the ionization temperature from an excitation temperature and ionization equilibrium.

Sargent (1964) has commented on the inadequacy of the temperature determinations by these writers and suggested that their Am stars are hotter. The result that would follow from Sargent's suggestion is that all abundances, except possibly those of Mg and Si,* would be raised. Most importantly, the Fe peak elements are overabundant (see also Hack 1966). However, the element/Fe ratios are relatively unaffected. Modern reanalysis of these Am stars would be helpful.

The analysis of five Am stars in the Hyades, 60 Tau, 63 Tau, 81 Tau, 16 Ori, and HD 30210, was made relative to a normal F0 V star, 45 Tau (Conti 1965*a*). A more elegant model atmosphere study of 63 Tau (van't Veer-Menneret 1963) showed agreement within a factor of two for all elements except Si and Ti where the

*The temperature-dependent part of the abundance determination for neutral lines is proportional to the difference between the ionization and excitation state of each line. This is small for Mg and Si for which only high excitation lines are observed.

difference was a factor of three. Results for ζ Lyrae A have been given by Praderie (1968) and for 22 Ser by Provost and van't Veer-Menneret (1969). These studies have used relatively high dispersion and the most complete fitting of models to observed continua and hydrogen line profiles. In all of these stars, the Fe group was overabundant. Hack (1956) has presented results for several other Am stars but had only moderate dispersion. Her results agree qualitatively with the high-dispersion studies.

Table I lists the MK spectral types, if known, and the photometric color indices for the Am stars analyzed at high dispersion. All of the MK spectral types are of Am subclass (a). From the Δk index, 8 Com is subclass (c). There is no analysis yet of a class (b) star but ν^1 Dra (shown in Fig. 1 with $\Delta k = -0.43$, $\Delta[m_1] \sim 0$) would be a good candidate.

TABLE I

STARS ANALYZED

Star	Ref	Spectral Type K	Spectral Type H	Spectral Type Metals°	$\Delta[m_1]$	Δk	$H\beta$
τ UMa	1,2,3	A5	F0	F6 II	−0.062	−0.56	2.764
8 Com	3				−0.074	+0.19	2.866
15 Vul	3				−0.017	−0.15†	2.840
HD 174704	4						
63 Tau	5,6	A1	F0	F5 IV	−0.054		2.783
60 Tau	6	A5	F0	F2	−0.028		2.757
81 Tau	6				−0.044		2.809
16 Ori	6	A2	A9	F2 IV	−0.059		2.820
HD 30210	6	A2	A7	F0 IV	−0.067		2.844
ζ Lyr A	7	A4	A7	F0	−0.045	−0.16	2.849
22 ser	8				−0.033	−0.41	2.860

°The high luminosity derived from metallic lines is probably due to metals being overabundant (see §V). The Sr II lines and other ionized lines are luminosity indicators.

†Estimated from Figure 2 of Henry (1969).

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3. Miczïaka et al. (1956)
4. Preston (1961)
5. van't Veer-Menneret (1963)
6. Conti (1965*a*)
7. Praderie (1968)
8. Provost and van't Veer-Menneret (1969)

The abundance results for the eleven Am stars, as quoted by the writers listed in Table I, are summarized in Table II and Figure 2. The star 63 Tau, studied by two writers, is shown twice. The data for four Am stars analyzed using the ionization equilibrium temperature procedure are plotted with open symbols. It can be seen, independently of the arguments above, that better agreement with the other Am stars would be found by raising all these abundances, except Mg and Si. Additionally, the $[m_1]$ for τ UMa and 8 Com suggest a large value for Fe/H, similar to that for 16 Ori.

Some elements are represented by very few lines. These are Na, Al, S, K, Co, Cu, and the heavier elements. The scatter among these elements is larger but not drastically more so than for the better determined elements. Aside from the deficiencies of Ca and Sc, which differ from star to star, there is a definite tendency for all the heavier element abundances to be systematically enhanced in a given star. The heaviest elements are the most enhanced.

The light elements Li and Be have not been identified in Am stars (Wallerstein and Conti 1969). Smith (1970) has reported preliminary results which suggest that C is generally deficient in Am stars. Praderie (1968) reported O to be deficient by a factor of two in several Am stars and N to be normal. Sargent and Searle (1962) found O to be slightly deficient in several Am stars. Aside from these studies and the results in Table II, no other detailed work on these astrophysically important light elements has been published. Further work is badly needed.

Table III comprises my estimate of the abundance situation generally found in Am stars. It is possible that all heavy elements are enhanced together. There is little quantitative correlation between the under- or overabundance of elements.

The star with the most extreme anomalies in this list is 16 Ori. The difference between the Ca and Fe content relative to normal A stars is a factor of 30. The star least extreme is 15 Vul, its difference is a factor of two. This star is the least extreme also, in its photometric indices. Other elements in these and other stars are more anomalous.

A number of early Am stars have also been analyzed with high dispersion, equivalent widths, model atmospheres, and the hypothesis of LTE. The prototype star is Sirius. Its atmospheric abundances

TABLE II

AM STAR ABUNDANCES

(Entries are log N with respect to normal stars.)

	(1)°	(2)°	(3)°	(4)°	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
C			−0.3								−0.3	
O									−0.7			
Na	+0.9		+0.5			+0.1	−0.1	+0.2	+0.4	−0.2	+0.4	+0.3
Mg	+0.2	−0.1	−0.2		−0.4	−0.2	−0.1	+0.1	+0.1	0	−0.1	+0.1
Al	+0.5	−0.1	−0.1			+0.2	+0.3	+0.8	+0.6	+1.1	−0.5	
Si	+0.2		+0.2		+0.7	+0.1	0	+0.3	+0.4	+0.5	+0.4	+0.3
S	−0.5					+0.5	+0.3	+0.3	+0.6	+0.8	+0.3	
K									−0.1			
Ca	−0.6	−0.5	−0.3	−0.3	−1.1	−1.0	−0.7	−0.1	−0.8	−0.4	−0.5	−0.6
Sc	−1.1	−0.9	−0.5	−1.8	−0.7	−1.0	−1.1	−1.1	−1.3		−0.7	−0.4
Ti	−0.2	−0.1	0	−0.3	+0.2	−0.3	−0.2	−0.1	−0.1	+0.1	0	+0.5
V	−0.4	−0.2	−0.1	−0.6	+0.2	+0.5	+0.5	+0.4	+0.5		+0.4	+0.4
Cr	+0.3	+0.1	−0.1	+0.4	+0.7	+0.9	+0.2	+0.6	+0.9	+0.5	+0.4	+0.6
Mn	+0.3	+0.1	0	+1.0	+0.1	+0.4	+0.2	+0.6	+0.6	+0.7	+0.5	+0.3
Fe	+0.2	−0.1	0	+0.3	+0.6	+0.4	+0.3	+0.3	+0.6	+0.4	+0.1	+0.5
Co		−0.2	−0.1			+0.5	+0.4	+0.1			+0.5	+1.0
Ni	+1.0	+0.4	+0.5		+0.9	+0.7	+0.6	+0.8	+1.0	+1.1	+0.6	+0.9
Cu						+1.0	+0.7	+0.9	+1.7	+1.7	0	+1.1
Zn	+0.7		+0.6			+1.3	+0.6	+1.0	+1.3	+1.5	+0.4	+0.6
Sr	0	+0.5	+0.1	−0.1	+0.9	+0.4	+0.3	+1.0	+0.7	+1.1	+1.6	+0.9
Y	+0.1	+0.2	+0.2	+1.0	+1.1	+1.1	+0.5	+0.6	+1.5	+1.0	+0.2	+1.1
Zr	−1.0	−0.3	−0.1	+0.2	+0.6	+0.2	+0.7	+0.5	+1.2	+0.5	+0.9	+0.3
Ba	+0.1	−0.1	+0.3	+0.3	+1.0	+0.8	+0.5	+1.3	+1.3	+0.9	+1.0	+0.8
Re				+0.7	+1.4		+0.7	+0.8	+1.0	+1.2		+1.1

°Entries for these stars are probably to be raised by a small factor according to the discussion in the text.

COLUMN IDENTIFICATION

(1) τ UMa
(2) 8 Com
(3) 15 Vul
(4) HD 174704
(5) 63 Tau (van't Veer-Menneret)
(6) 63 Tau (Conti)
(7) 60 Tau
(8) 81 Tau
(9) 16 Ori
(10) HD 30210
(11) ζ Lyr A
(12) 22 Ser

TABLE III

SUMMARY OF AM ABUNDANCES

	Well Determined	Not as Well Determined
Deficient	Ca, Sc	C, O
Normal	Mg, Ti	N, Na, K
Possibly overabundant	Si, V	Al, S, Co, Zr
Overabundant	Cr, Mn, Fe, Ni	Cu, Zn, Sr, Y, Ba, RE

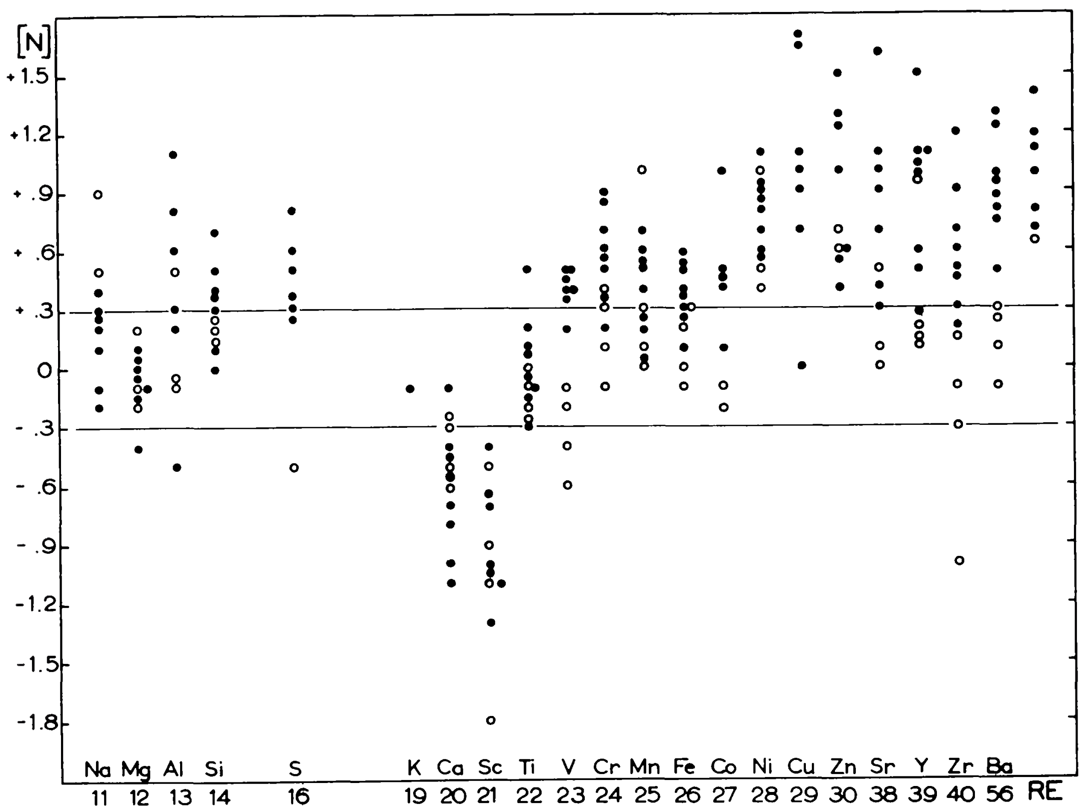

FIG. 2 — Logarithmic abundances for Am stars with respect to normal stars (taken from Table II). Open circles are stars analyzed with the ionization equilibrium procedure; filled circles are stars analyzed using model atmospheres. Better agreement between the groups of stars is obtained by raising the abundances of the former group by a factor of two to three, as discussed in the text. The stars differ in their Ca and Sc abundances but there is a uniform enrichment tendency for the heavier elements. A normal star would have derived abundances within a factor of two of normal (between the horizontal lines).

TABLE IV

Early Am Star Abundances

(Entries are log N with respect to normal A stars.)

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
C	−0.8	−0.4	−0.1	−0.5	−0.4			
O	+0.3	−0.6				0		
Na	+0.4					+0.6	−0.1	−0.5
Mg	+0.6	−0.4	−0.1	−0.2	−0.1	+0.4	−0.1	−0.1
Al	+0.9	+0.6	−0.2	−0.1	+0.1			
Si	+0.9	+0.2	−0.2	−0.1	0	+0.3	−0.2	
S	+0.6							
Ca	+0.1	−0.8	−0.1	−0.4	−0.2	0	0	<-1.0
Sc	+0.3	−1.8	−0.4	−0.5	−0.1	−0.4	+0.1	<-0.7
Ti	+0.7	−0.4	0	0	0	+0.1	0	−0.4
V	+0.7		−0.2	−0.2	+0.1	0	−0.1	+0.2
Cr	+1.1	+0.1	−0.2	0	−0.1	+0.2	+0.1	0
Mn	+0.6	−0.1	−0.1	−0.1	−0.1	+0.4	0	
Fe	+0.9	0	0	−0.2	+0.1	+0.2	0	0
Ni	+0.9	0	+0.4	+0.4	+0.5	+0.6	+0.1	−0.2
Zn	+1.0	+1.0						
Sr	+1.5	+0.3	+0.5	+0.3	+0.7	+0.6	+0.2	+0.2
Y	+0.9	+0.1	+0.5	0	+0.6	+0.2	+0.1	
Zr	+0.8		+0.2	+0.2	+0.5	+0.5	+0.3	
Ba	+1.1	+0.5	+0.1	+0.4	+0.5	+0.6	+0.2	+0.1

COLUMN IDENTIFICATION

(1) Sirius - Strom, Gingerich, and Strom (1968)
(2) 68 Tau - Conti and Deutsch (1966)
(3) HD 22615 - Conti and Strom (1968*a*)
(4) HD 23631 - Conti and Strom (1968*a*)
(5) HD 24368 - Conti and Strom (1968*a*)
(6) o Peg - Conti and Strom (1968*b*)
(7) η Vir primary - Conti (1969*b*)
(8) η Vir secondary - Conti (1969*b*)

have been determined numerous times (e.g., Kohl 1964; Strom, Gingerich, and Strom 1966, 1968).

Results for other early Am stars are summarized in Table IV and Figure 3. The general pattern of anomalies shown in Figure 2 is repeated here. The Am stars in the Pleiades are remarkably similar to 15 Vul in their abundances (cf. Tables II and IV).

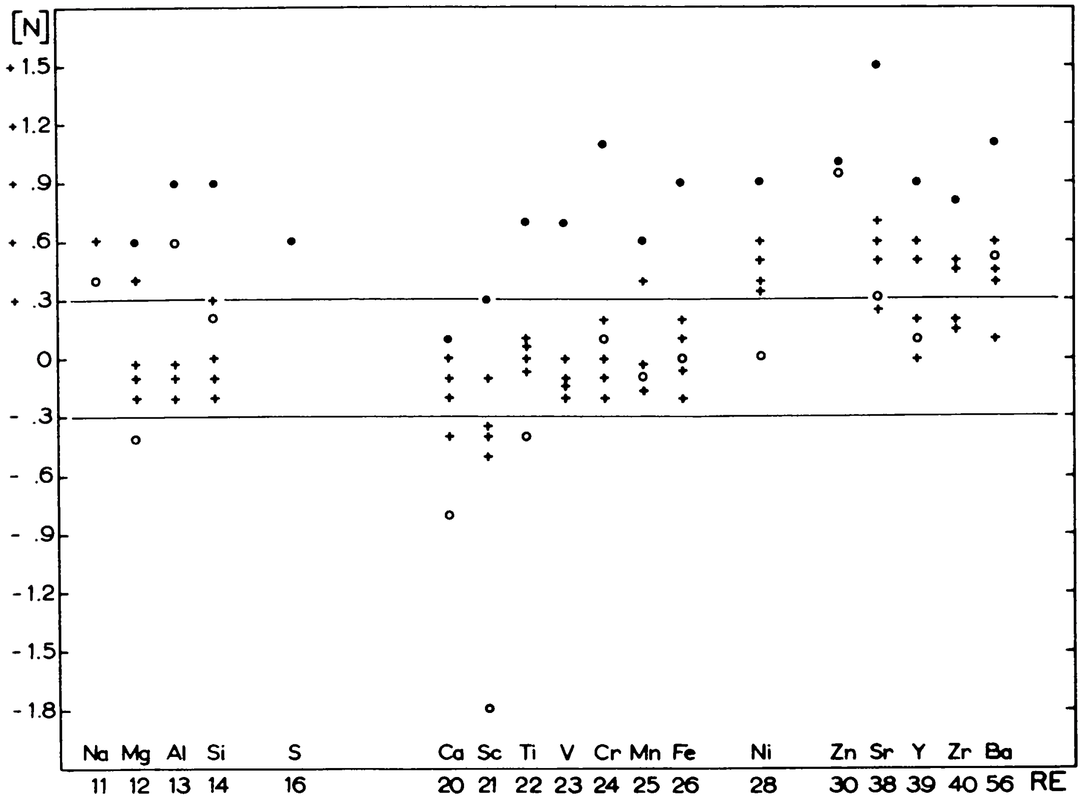

FIG. 3 — Logarithmic abundances for early Am stars with respect to normal A stars (taken from Table IV). The filled circles represent Sirius; the open circles, 68 Tau; the crosses, the stars in the Pleiades and o Pegasi. The trend of abundances of these stars is similar to that shown in Figure 2. A normal star would have derived abundances within a factor of two of normal (between the horizontal lines).

Sirius appears to be a subclass (c) Am star, while 68 Tau is subclass (b). It may be important that there is no clear case as yet, of an early Am star as extreme in its abundance anomalies as, say, 63 Tau.

A most intriguing question then arises. Is this because the most extreme Am stars occur only in the late A's, or is it an age effect? Could the Am phenomenon become more pronounced with age? For example, the Am phenomenon in the Pleiades is not as pronounced as in the Hyades. Is this a spectral type, age effect, or due to a difference in cluster rotational velocity? A more precise study of such questions should be made. A promising start could be made using Henry's (1969) indices in star clusters of differing ages and with different rotational velocities.

Conti (1969*b*) derived the abundances for the spectroscopic binary early Am star, η Virginis. In this system, only the secondary, of type about A4, appears to be Am. The primary, of type A2, has several heavy elements marginally enhanced. Toy (1969) has reported an analysis of the double-line early A star β Aur and finds that both stars show Am characteristics.

VI. Explanations of the Am Phenomenon

A. Anomalous Atmospheres

The most perplexing aspects of the Am phenomenon have been the apparent deficiencies of some elements and the excesses of other elements. Greenstein (1948) showed that the Am stars were not composite spectra, i.e., composed of an A and an F star. Greenstein (1949) also showed that dilution effects were not present, therefore a shell was unlikely. The two usually deficient elements, Ca and Sc, have their second ionization potentials near that of H. This suggested that perhaps there was an excess second ionization of these elements. Greenstein (1949) showed that other effects, such as emission in the Balmer lines would then be expected but were not present. In addition we have seen that Y is always in excess, yet its second ionization potential is between that of Sc and Ca. It appears that this process alone will not explain the Am phenomenon.

Another explanation also invoking excess second ionization was advanced by Böhm-Vitense (1960). She suggested that the Am stars had an abnormally low electron pressure in the outer parts of the atmosphere. With this approach she could explain the weakness of the K line. Conti (1965*a*) investigated this problem with his empirical models. It was possible, by arbitrarily changing the gravity in the outer parts of the atmosphere, to change the Ca abundance, but the Ca/Fe ratio was unaffected. Models of arbitrarily higher boundary temperature and arbitrarily higher He abundance also had no effect on the Ca/Fe ratio. It appears that LTE models using ionization effects alone cannot explain the Am phenomenon.

At this point a word must be said about departures from LTE. Since a complete, physically consistent non-LTE theory has not been derived for any star, even the sun, it is possible that in Am star atmospheres, there is some non-LTE effect that results in these abundance anomalies. This effect, if present, does not manifest itself in emission lines, peculiar line profiles, or in continuum measures of these stars. Line strengths of an element from different ionization and excitation states, and from metastable and permitted states, give consistent results. If some non-LTE effect is involved in a fundamental way with the Am phenomenon, then it must be present without violating these observational data. The most that can be said about non-LTE for Am stars is that it is possible, but unproven.

B. Anomalous Abundances

We have seen that it is unlikely that the observed deficiences and overabundances of elements in Am stars are due to atmospheric effects (other than non-LTE). More likely real anomalies in composition are present. Nuclear processing has been suggested and the consequences developed in some detail by Fowler et al. (1965). It is suggested that a drastic reorganization of material has occurred in the stellar interior due to nuclear reactions. This hypothesis has the advantage that there are a number of free parameters to play with. Often overabundances of heavy elements are produced in the reactions that may take place. One basic objection to nuclear processing for Am stars is that deficiences of Ca and Sc have never been found in these processes, nor do the observed overabundances match predictions well. It could be supposed, however, that other nuclear processes might be found.

There are several conditions under which nuclear processing can occur. I will argue that all, except the last, are unsuitable for Am stars on grounds *other* than not matching the anomalies.

1. Reactions In Stellar Interiors Plus Mixing

Fowler et al. (1965) suggested that a reorganization goes on in the interior of a star when the star is a red giant and then the changed composition is mixed to the surface. It then follows that Am stars have returned from the red-giant branch. This proposal can be dismissed on age arguments (see §II *B*) and the observed presence of Am stars in close binary systems. In close binary systems, stars cannot evolve to the red-giant stage in a normal manner: Mass exchange between the components must take place.

2. *Reactions In Stellar Interiors Plus Mass Exchange*

The latter argument led van den Heuvel (1968*a,b*) to develop, in detail, the suggestion that Am stars are the products of evolution in a close binary system. The Am star was supposed to have once been the secondary in a normal binary. The original primary evolved first, perhaps castastrophically, and deposited its processed material on the surface of the secondary, making it Am. The original primary is now an undetectable white dwarf. In this way the high frequency of binaries among Am stars and the slow rotation (a product of the mass exchanges) are naturally explained. Also, there is an obvious relation of Sirius, with a known white dwarf companion, to this scheme.

Two objections to van den Heuvel's theory that Am stars are evolved binaries have already been cited: namely, that the Am binaries form a natural and necessary continuation of binary frequency along the main sequence (see §II *D*) and the probable presence of Am stars in young clusters (see §II *B*).

Another objection is the presence of numerous double-line Am systems, in which the secondary is not a white dwarf. These systems, under van den Heuvel's hypothesis, must contain a third, evolved component. Although a careful search has not yet been made, there is no evidence that any double-lined spectroscopic binary Am systems are triple.

3. *Reactions On Stellar Surfaces*

Searle and Sargent (1967) have suggested that reactions on stellar surfaces, during the time of star formation, might be important for the anomalies in Ap stars. Could this also be the case for the Am stars? One could imagine, for example, that the contraction phase for binary stars could well be a time of unusual conditions. Binaries with periods less than 100 days presumably were in contact during contraction. Searle and Sargent (1967) have pointed out that the sharp-line stars in the A spectral range are uncommon and suggest that the process of slowing the rotation of these stars is related to their anomalies.

This hypothesis fits all the data presently available for the Am stars, in that binaries are common, the stars are all slow rotators, the anomalies could well be confined to the surface layers, etc.

The only discouraging aspect to this suggestion is the complete lack of a nuclear processing theory to account for the anomalies. An important prediction of the theory would be that Am binaries with short periods should have similar Am anomalies, because they presumably interacted during the contraction phase. A study of this question is presently underway by D. Stickland. At present this theory is tenable, but unproven.

4. Physical Separation Processes

If nuclear processes have not altered the surface composition of Am stars, what else could have done so? Praderie (1967*b*) suggested that thermal diffusion and gravitational separation were responsible. She calculated that this process would operate very quickly in stars and the sun. The heavier elements would tend to sink from the visible atmosphere. She proposed that in the Am stars these processes did not operate. In this context, the Am stars have the "normal" compostion and the sun and other stars are deficient in heavy elements. Schatzman (1969) has rediscussed the problem of diffusion with a more complete physical picture. He shows that the tendency for gravitational separation is larger for F stars than for the sun, and that a diffusion barrier below the convective zone would be inefficient because of turbulence mixing. Schatzman finds that the slightest amount of turbulence mixing will impede gravitational separation. He points out that the turbulence would also be enhanced by rotation.

Michaud (1970) has pointed out that if a radiation pressure term is considered in separation processes, it would be possible to concentrate elements at the top of the atmosphere and enhance their abundance. He shows that this process is efficient for heavy elements, normally in lower abundance and having many spectral lines. Light elements with a high abundance and few lines are not affected by radiation pressure and then sink in the atmosphere due to gravity. Although Michaud specifically discussed this process for Ap stars, one wonders whether or not it might be important for Am stars.

One difficult problem with Michaud's suggestions is that the atmosphere must be extremely stable against turbulence mixing for these processes to be efficient. On the face of it, it would seem that Am stars have high turbulence (see §IV), although this is not peculiar to them. On the other hand, I would like to stress that this turbulence is only a parameter from a curve-of-growth study and its physical relation to a mixing process has not been established. Am stars certainly do rotate and, as Schatzman (1969) points out, this should enhance mixing. On the other hand, the calculations relating these parameters physically have not yet been made.

My feeling is that physical separation processes could well prove to be very important in understanding the Am phenomena although very much more work is needed on the theoretical aspects. If these processes are important we might observe some correlation of Am peculiarities with effective temperature or luminosity, or perhaps rotation. Such observations have been suggested (see §II *E*) but more work on this problem is needed.

VII. Conclusions

1. Am star atmospheres are characterized by either deficient Ca (Sc) or overabundant heavier elements, or both.
2. These anomalies are probably indicative of real abundance differences and cannot be explained by known physical atmospheric effects.
3. Although Am stars have a high microturbulence, this parameter is not peculiar to them as other stars in the same spectral region share this characteristic.
4. The Am star atmospheres are anomalous only in their composition.
5. As a group, Am stars are slowly rotating, due in many cases to their being members of close binaries.
6. Am stars are mostly unevolved, and their anomalies could well be acquired early in their youth.
7. The Am phenomenon is found in only a limited region of the HR diagram, near to the main sequence, and between F0 and A0.
8. The different behavior of Ca (Sc) and other metals suggests that two different, but possibly related, processes are involved in the Am phenomenon.
9. Nuclear processes in stellar interiors or on the surfaces of Am stars do not seem to be involved in the Am problem.
10. Physical separation processes may prove to be the key to our understanding of these curious stars.

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