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METALLIC-LINE A STARS AND PULSATION

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ABSTRACT

The short-period variability of Am stars has been investigated. In the Praesepe and Hyades clusters all of the 11 Am stars examined were nonvariable. Of twenty-seven stars with normal spectra in these clusters, ten were δ Scuti variables with amplitudes larger than 0.010 mag, four were possibly variable, and thirteen stars were nonvariable.

Data collected for a large sample of the field and cluster stars falling within the δ Scuti instability strip show that the classical Am stars are stable against pulsation whereas more than 30 percent of the normal stars are variable. The connection between pulsational stability and Am characteristics outside the classical Am region is less clear. Model-atmosphere abundance analyses find the Am characteristic in the late variables outside the classical Am region, δ Sct and ρ Pup, less pronounced than previous curve-of-growth analyses. The metal underabundance of the variable δ Del is confirmed by the fine analysis.

The hypotheses that (i) Am characteristics tend to inhibit pulsation or (ii) pulsation destroys the observable Am characteristics (which would be in a thin surface layer only) are discussed briefly.

I. INTRODUCTION

The lower instability strip, where the short-period δ Scuti variables are found, extends from spectral type A4 to F2 on the main sequence. Consequently, a large portion of the metallic-line A stars are situated inside the instability strip. Since some 20 percent or more of the stars inside the lower instability strip have detectable short-period light variations, the question arises whether the Am stars share this property. Should they not, this discovery would be another important difference between Am and normal A stars.

Before this investigation only little was known about the relationship between Am characteristics and pulsation: (i) A curve-of-growth analysis of three *late* δ Scuti variables by Bessell (1969) indicated that ρ Pup and δ Sct might have abundances similar to those found in Am stars, whereas δ Del was found to be abnormally weak in Ca and Sc as well as Fe. This analysis, however, was criticized somewhat by Reimers (1969) since model atmospheres had not been used. In § III we have reanalyzed Bessell's data through model atmospheres. (ii) Danziger and Dickens (1967) included four Am stars in their search for short-period variability. There was an *indication* that these stars did not vary in light. (iii) The survey by Breger (1969*a*, *b*) found that, out of ten Am stars inside the instability strip, one (HR 114) was variable. This proportion was in agreement with the expected number as judged from non-Am stars. However, an 8 Å mm^{-1} spectrum, kindly taken by L. V. Kuhi with the Lick 120-inch reflector, shows that HR 114 is a normal late A star. (iv) Walker and Jones (1969) suspect the Am star HR 7431 to have short-period variations in radial velocity. This variability, however, must still be regarded as very uncertain. (v) Two known δ Scuti variables, HR 5017 and HR 3265, have a large m_1 index which could be caused by high metal abundance or microturbulence. Such a high m_1 index is also characteristic of many Ap and Am stars. However, HR 3265 has been classified by Cowley *et al.* (1969) as a normal F2 III star, and a spectrum taken of HR 5017 by Smith (1970) also appears normal. Hence these two stars appear to be normal despite their anomalous m_1 index.

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1970ApJ...162..597B

Because of the very uncertain observational situation, it seems desirable to investigate the problem of the variability of Am stars more closely. Such an investigation is severely limited by our present lack of understanding of the Am phenomenon. It is quite likely that several subgroups of Am stars do exist (Conti 1970) with various degrees of weak Ca and Sc lines, as well as weak, normal, or strong metallic lines. For the purposes of this investigation we shall consider two different types of A and F stars with unusual line strengths:

i) The classical Am stars. In accordance with Abt and Bidelman (1969), these stars occur between A4 and F1 with luminosity classes IV and V.

ii) Other A/F stars outside the classical Am region, but possibly still inside the instability strip, with unusual line strengths. This includes the two known variable δ Delphini stars (δ Del and 14 Aur). The star δ Del is underabundant in Ca as well as most (other) metals by a factor of 2 or more. This group would also include δ Sct and ρ Pup, should these stars really have abnormal abundances. Classifications to determine Am characteristics were taken from the new catalog by Cowley *et al.* (1969), and from listings by Dickens, Kraft, and Krzeminski (1968) for the Praesepe Cluster, Morgan and Hiltner (1965) for the Hyades Cluster, and Kraft (1965) for the Coma Cluster.

II. NEW OBSERVATIONS

All stars in the Praesepe Cluster in or near the instability strip were photoelectrically observed for short-period variability. Several stars in the Hyades Cluster were also observed. The 36-inch and 16-inch telescopes of the Kitt Peak National Observatory were used. For each program star (P), two close comparison stars (C_1, C_2) of similar magnitudes and colors were chosen. These comparison stars were often other program stars already known to be constant. This is justified as long as only the program star is variable. Each single observation consisted of twelve successive 10-second integrations. The group of three stars was observed in the V-magnitude for up to 6 hours in the successive cycle C_1, P, C_2. The observing technique has been described in detail by Breger (1969*a*). It should be noted that the Praesepe Cluster is ideal for this investigation because of the close proximity of many suitable comparison stars in the cluster. The higher photometric accuracy should result in the discovery of several short-period variables with small light amplitudes between 0.01 and 0.02 mag. Furthermore, the Praesepe and Hyades Clusters contain many Am as well as normal A stars.

The results shown in Table 1 were, apart from the present observations, the magnitudes and *uvby* colors were taken from Crawford and Barnes (1966, 1969). The constancy of the measured light through the V-filter is given in column (5), where s denotes the mean absolute error per *single* observation relative to the comparison stars. Ten new variables were found. Their periods ranged from 50 minutes to 3 hours. This range is typical for δ Scuti variables. Since the elements of the variation of these stars are not relevant to the present discussion, they are omitted here. An example has already been given by Breger (1969*a*, Fig. 1), where the light curve of the Praesepe star KW 323 has been plotted against the observations of the comparison stars.

It has to be emphasized that many "constant" stars in the instability strip could well be variables with very small, undetected amplitudes. Except for a few Am stars, the observations are insufficient to detect possible amplitudes of about 0.005 mag. The residuals of four stars, however, were systematic enough to suggest regular light variability with amplitudes less than 0.01 mag, and these cases have been noted under "Remarks."

Of the twenty-seven non-Am stars inside the instability strip, ten were found to be definitely variable, four possibly variable, and thirteen constant. On the other hand, all nine Am stars inside and two Am stars outside the instability strip were constant. This indicates that, at least in the Praesepe and Hyades Clusters, pulsation and the Am phenomenon are mutually exclusive.

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1970ApJ...162..597B

TABLE 1

VARIABILITY OF STARS IN THE PRAESEPE AND HYADES CLUSTERS

Star (1)–(2)		V (3)	$(b-y)$ (4)	Constancy s (mag) (5)	Time Observed (hours) (6)	Remarks (7)
KW	HD					
				Praesepe		
38.....	73161	8.70	0.188	0.002	1.4	
40.....	73174	7.70	0.112	0.002	4.1	Am
				0.001	2.8	
45.....	73175	8.26	0.131	variable	...	
50.....	73210	6.75	0.120	0.001	4.7	
114.....	73345	8.15	0.122	0.002	2.2	Small variability
				0.001	2.0	possible
124.....	73397	8.99	0.208	0.001	2.4	
				0.001	4.4	
143.....	73430	8.31	0.127	0.001	4.4	
150.....	73449	7.45	0.157	0.001	2.8	
				0.003	0.8	
154.....	73450	8.50	0.149	variable	...	
203.....	73574	7.73	0.126	0.001	1.4	
				0.003	6.1	
204.....	73575	6.66	0.153	variable	...	
207.....	73576	7.67	0.104	variable	...	
224.....	73618	7.32	0.104	0.003	1.8	Am
				0.001	2.1	
				0.001	4.6	
226.....	73616	8.89	0.209	0.001	2.4	
				0.002	2.2	
229.....	73619	7.54	0.143	0.002	4.4	Am
				0.003	1.8	
				0.001	2.2	
				0.001	4.6	
				0.002	3.4	
				0.001	4.0	
271.....	...	8.81	0.192	0.001	2.4	
				0.001	2.6	
276.....	73711	7.54	0.075	0.001	2.1	Am
				0.003	1.4	
				0.003	2.3	
279.....	73709	7.70	0.099	0.001	2.8	Am
284.....	73712	6.79	0.161	0.003	2.3	
				0.001	2.1	
286.....	73730	8.02	0.113	0.001	2.6	Am
				0.002	2.8	
292.....	73729	8.19	0.198	variable	...	
300.....	73731	6.30	0.091	0.003	2.3	Am
318.....	73746	8.66	0.181	0.001	1.0	
				0.002	4.4	Small variability
						possible
323.....	73763	7.80	0.130	variable	...	
328.....	73785	6.85	0.109	0.001	4.7	
				0.001	2.1	
340.....	73798	8.48	0.147	variable	...	
348.....	73819	6.78	0.091	0.001	2.1	
				0.003	2.4	
350.....	73818	8.71	0.190	0.002	3.4	Am
				0.002	4.4	
				0.001	2.4	

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1970ApJ...162..597B

TABLE 1—*Continued*

Star (1)–(2)		V (3)	$(b-y)$ (4)	Constancy s (mag) (5)	Time Observed (hours) (6)	Remarks (7)
				Praesepe		
KW	HD					
370.....	73854	9.04	0.218	0.001	4.4	
375.....	73872	8.33	0.129	0.002	2.8	
385.....	73890	7.91	0.144	0.002	2.2	Small variability possible
				0.002	4.6	
429.....	73993	8.54	0.194	0.003	1.0	
				0.002	2.8	
445.....	74028	7.96	0.120	variable	...	
449.....	74050	7.91	0.115	variable	...	
				Hyades		
VB	HR					
33.....	1356	5.2	0.126	variable	...	
34.....	1358	6.2	0.292	0.002	4.9	
				0.001	3.0	
38.....	1368	5.7	0.196	0.002	3.0	Am
45.....	1376	5.6	0.180	0.001	3.0	Am
53.....	1385	6.0	0.242	0.002	3.2	
57.....	1391	6.5	0.314	0.001	3.8	
74.....	1414	5.1	0.114	0.001	3.8	
83.....	1428	5.5	0.142	0.002	4.0	Am
84.....	1430	5.4	0.154	0.002	3.8	
95.....	1444	4.7	0.144	0.002	3.0	
103.....	1472	5.7	0.191	0.003	3.3	
				0.002	3.4	
111.....	1507	5.6	0.149	0.002	3.0	Small variability possible

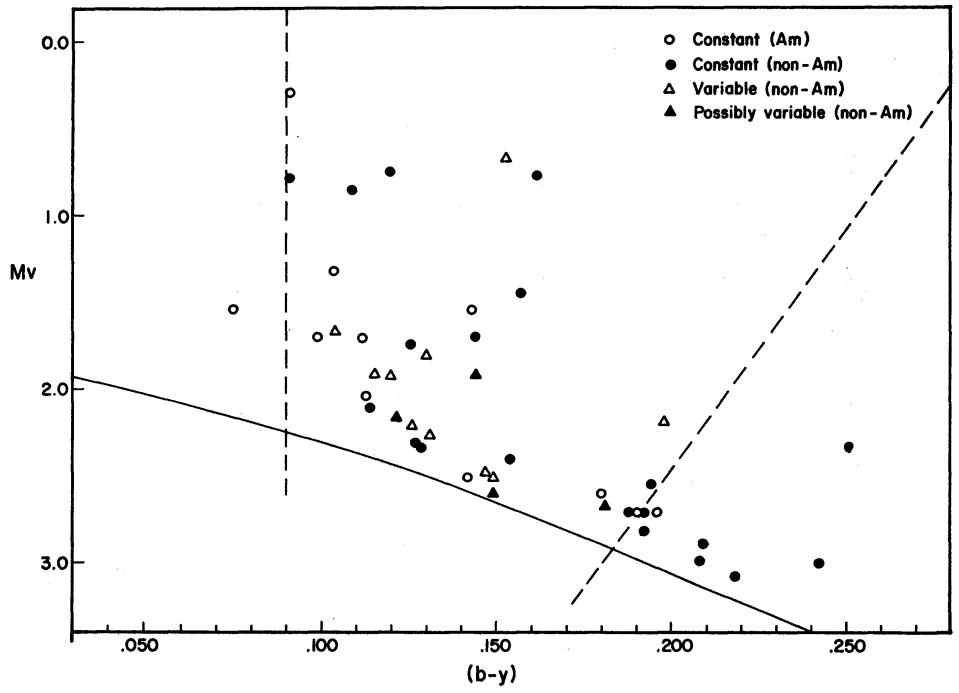


FIG. 1.—Light variability as a function of luminosity and color in the Praesepe and Hyades Clusters. We note that all Am stars are constant. *Solid lines*, zero-age main sequence; *broken lines*, observed borders of the lower instability strip.

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1970ApJ...162..597B

III. ABUNDANCES OF δ DEL, ρ PUP, AND δ SCT

The curve-of-growth analysis of δ Del, ρ Pup, and δ Sct by Bessell (1969) has indicated a low [Ca/Fe] ratio for all three stars. The variable δ Del, which is the prototype for its class of spectral peculiarity, appeared to be underabundant in all metals, while ρ Pup and δ Sct seemed to share the high Fe abundance of the (hotter) Am stars. A more detailed model-atmosphere analysis of δ Del by Reimers (1969) has confirmed the underabundance of metals but not the low [Ca/Fe] ratio.

Model-atmosphere abundance analyses have been carried out by means of a program and ATLAS model atmospheres kindly made available by S. E. Strom. This technique has been applied by Strom (1969), where the references for the *gf*-values used are also given. The effective temperatures and gravities of the three variables and the two standard

TABLE 2

FINE-ANALYSIS RESULTS

	STANDARD STARS		VARIABLES		
	η Lep	α CMi	δ Del	ρ Pup	δ Sct
T_e (°K)	7000	6650	6950	7000	7050
log g	3.5	4.0	3.2	3.3	3.3
V_t	2.7	3.3	4.3	6.0	5.5
[Ca I]	−0.02±0.06	+0.03±0.06	−0.46±0.07	+0.18±0.05	+0.20±0.09
[Sc II]	−0.04±0.23	+0.02±0.12	−0.59±0.20	+0.09±0.15	+0.35±0.18
[Ti I]	−0.03±0.19	+0.02±0.13	...	+0.28±0.10	+0.20±0.17
[Ti II]	−0.02±0.10	+0.02±0.10	−0.49±0.10	+0.23±0.06	+0.16±0.10
[Cr I]	−0.04±0.10	+0.02±0.06	−0.16±0.07	+0.37±0.08	+0.30±0.13
[Cr II]	−0.08±0.12	+0.05±0.06	−0.35±0.06	+0.34±0.10	+0.05±0.09
[Fe I]	0.00±0.04	0.00±0.04	−0.25±0.04	+0.42±0.04	+0.24±0.05
[Fe II]	+0.03±0.06	−0.04±0.11	−0.21±0.07	+0.41±0.05	+0.24±0.10
[Mn I]	+0.02±0.13	−0.02±0.15	...	+0.28±0.10	...

stars (α CMi and η Lep) were determined from the available Hγ profiles and spectrophotometry (Bessell 1969; Breger and Kuhi 1970). Small changes in gravity and temperature were then applied to give reasonable agreement with stellar excitation and ionization equilibria. These shifts are within the expected uncertainties due to uncertain line-blocking coefficients and do not significantly influence the conclusions of our analysis.

The results based on Bessell's (1969) equivalent widths are shown in Table 2. The errors shown are *internal* standard deviations in the mean. There is excellent agreement between the abundances derived for the two standard stars η Lep and α CMi. All abundances given in Table 2 are relative to a weighted mean between the two stars.

Our fine analysis confirms the previous results of low metal abundance of δ Del, as well as the slightly low [Ca/Fe] ratios for δ Del and ρ Pup. The metals of ρ Pup appear to be enhanced by a factor of 1.5 to 2.5. While the metals of δ Sct also appear to be somewhat enhanced, we cannot find any evidence for a low [Ca/Fe] ratio as found in the classical Am stars.

In conclusion, our model-atmosphere abundance analysis confirms the metal underabundance found in δ Del, but finds Am-like characteristics in δ Sct and ρ Pup less pronounced than those found by Bessell. The question of unusual atmospheric abundances outside the region of classical Am stars certainly requires much more extensive investigation.

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1970ApJ...162..597B

IV. DISCUSSION

The present results for the Praesepe and Hyades Clusters can be generalized by also considering previous variability investigations. Apart from the data mentioned in the Introduction, data on field stars taken from lists given by Millis (1967, 1970) have also been included, while Breger (1909*c*) has examined the variability of the stars in the Coma Cluster. Stars that had no available two-dimensional spectral classification were rejected from this investigation.

Figure 2 shows that none of the nineteen classical Am stars inside and seven classical Am stars outside the instability strip is variable. The positions of the possible metallic-line F stars, δ Sct and ρ Pup, which have been discussed earlier, are also shown. It is clear (so far) that no classical Am stars are known to be pulsating. On the other hand,

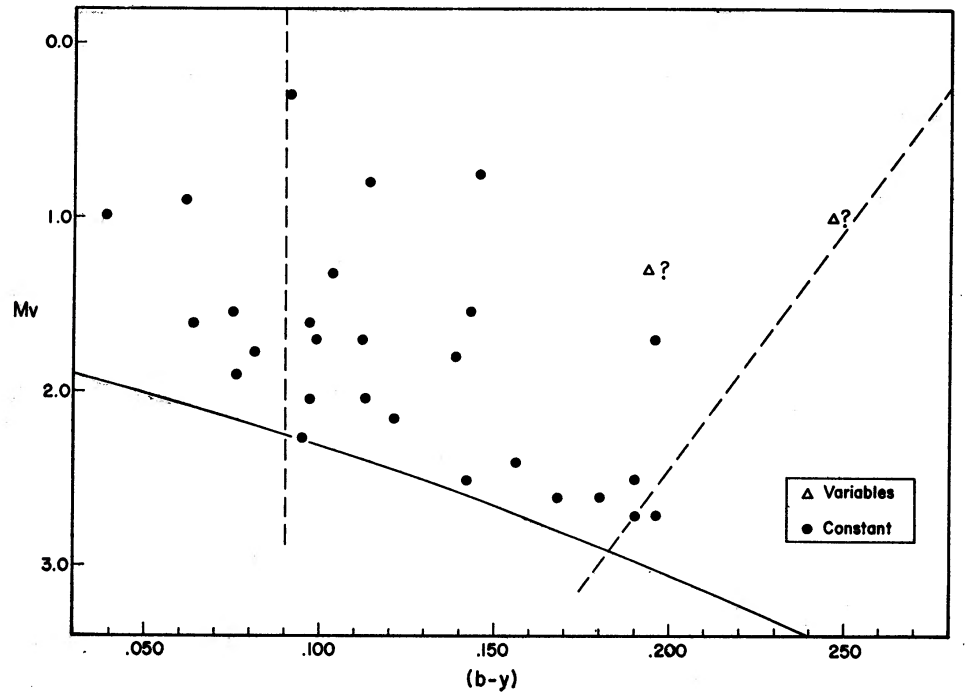


FIG. 2.—Variability as a function of luminosity and color for known Am stars examined for variability. The two triangles refer to δ Sct and ρ Pup which are F stars with marginal Am-like abundances (see text). The metal-deficient δ Del stars have been omitted from both Figs. 2 and 3.

thirty-one out of ninety-three non-Am stars shown in Figure 3 are δ Scuti variables. Because of the large number of δ Scuti variables with very small amplitudes, it is possible that many of the constant stars are actually pulsating with presently undetectable amplitudes. This argument could, of course, also be applied to the Am stars. However, since the frequency-amplitude relationship inside the lower instability strip seems to follow an exponential increase in number with decreasing amplitude (Breger 1969*b*), the absence of *any* Am stars with detectable light variation larger than 0.005 mag also indicates that the majority of the classical Am stars cannot pulsate with light amplitudes in excess of 0.002 mag, if at all.

We have implicitly assumed that we have selected stars inside the instability strip, whose boundaries are set by the effective temperature. There exist two possible effects which can influence the transformation between the observed $b - y$ colors and effective temperature: (i) possible binary companions, since most Am stars are binary systems

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1970ApJ...162..597B

(Abt 1965; Abt and Bidelman 1969) and (ii) line blanketing. However, since the less luminous companion in the Am stars cannot be more evolved than the primary (except possibly for semidetached systems) and should lie on the main sequence, only a small increase of several hundredths of a magnitude in $b - y$ would result. The effect of the larger line blocking in the Am stars than in normal A stars on the $b - y$ index can be determined from measurements by Baschek and Oke (1965) and is also found to be small: $\delta(b - y) \lesssim 0.03$ mag. Furthermore, it acts in the opposite direction from that of the duplicity effect. Since these effects are insignificant, we propose that most, possibly all, classical Am stars near the main sequence in the instability strip do not pulsate.

The fact that stars with classical Am characteristics do not pulsate may not be directly related to the physical state of the Am phenomenon. It could be argued that secondary

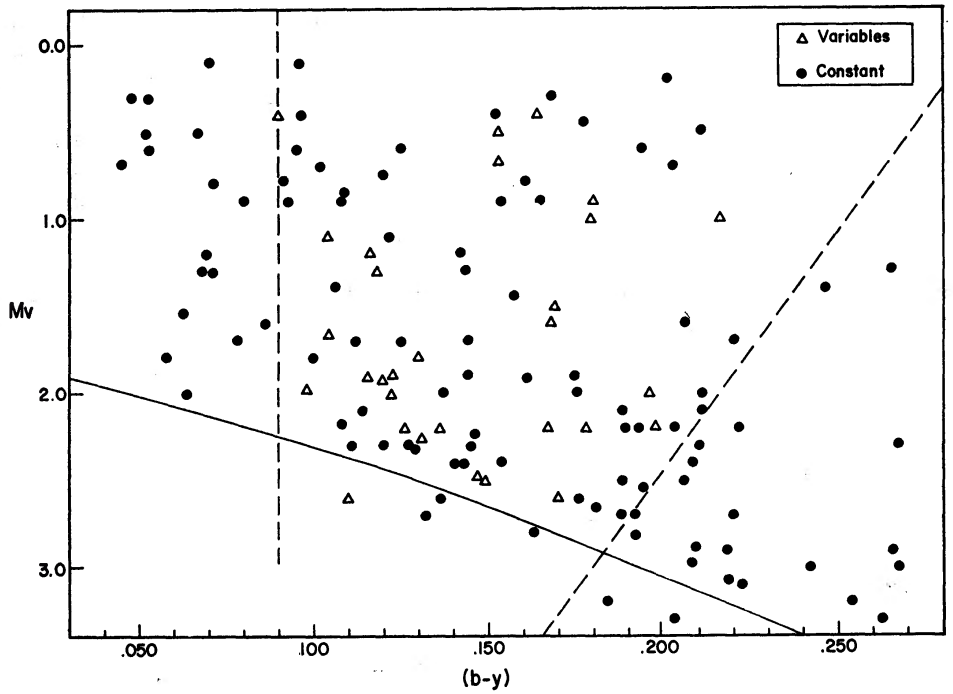


FIG. 3.—Same as Fig. 2, but for known non-Am stars examined for light variability and with a three-dimensional spectral classification.

characteristics associated with Am stars such as close companions and/or low rotational velocity could inhibit pulsation. However, δ Scuti variables in close non-Am binary systems are known, e.g., HR 8584. Should arguments similar to those presented by Fitch (1967) be correct, pulsation in fact should be enhanced by tidal interaction between the primary and the companion. Hence, this explanation is not likely.

Rotation has an important influence on pulsation in the sense that, for stars 2 mag above the main sequence, low rotational velocity favors pulsation (Breger 1969*b*). Am stars, however, which rotate slowly, are found closer to the main sequence, where the δ Scuti variables appeared to have a *slightly* higher rotational velocity than the nonvariable stars ($v \sin i = 137 \pm 10$ versus 102 ± 7 km sec^{-1}). This small difference can now be explained by the previous inclusion of a few nonvariable and low $v \sin i$ Am stars in the sample. Once these stars are excluded, we conclude that near the main sequence the incidence of pulsation is not correlated with rotational velocity.

It is possible that some subsurface effects (such as magnetic fields) could cause both the observed stability and abundance anomaly in Am stars. Apart from that, the ques-

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1970ApJ...162..597B

tion arises whether (i) Am composition effects or atmospheric stratification tend to inhibit pulsation or (ii) pulsation destroys the observable anomalies. This might be directly related to the question whether in an Am star the observed abundance anomalies apply to the whole star or are just an atmospheric effect.

The first hypothesis would imply that Am stars are structurally more stable against pulsation than is the case for normal A stars. The stars in the lower instability strip have nearly equal pulsational excitation and damping, which results in zero or small amplitudes. Especially if Am stars do have a generally higher metal content throughout, this might provide the small push toward overall stability. Theoretical calculations to evaluate this effect need only determine the direction of that push. If, on the other hand, the observed Am characteristics apply only to a thin surface layer, it is difficult to see how this would affect the stability of the star significantly.

The second hypothesis might apply if the observed abundance anomalies are only surface effects, possibly caused by surface nuclear reactions, binary mass exchange, or the Michaud (1969) effect. Pulsation could provide a mixing mechanism that might eliminate these anomalies.

The pulsational stability of classical Am stars offers the possibility of providing further information about the cause of the Am phenomenon. Because of insufficient data, no conclusions about the relation between pulsational stability and possible Am-like surface abundances *outside* the classical Am region can yet be made.

We are extremely grateful to Dr. S. E. Strom for the use of his model-atmosphere abundance analysis program and to M. Smith and P. S. Conti for communication of their unpublished results.

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