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METALLICISM AND PULSATION: THE MARGINAL METALLIC LINE STARS

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ABSTRACT

Evidence is presented that HR 4594 and HR 8210 are pulsating marginal Am stars. It is suggested that (i) classical Am stars do not pulsate, (ii) evolved Am stars may pulsate, and (iii) marginal Am stars may pulsate. It is further suggested that, within the Am domain, temperature, age, rotation, and pulsation are sufficient to determine whether a star will be Am, marginal Am, or spectrally normal.

Subject headings: photometry — stars: δ Scuti — stars: individual — stars: metallic-line — stars: pulsation

I. INTRODUCTION

In their spectral classification of the A stars in the *Catalogue of Bright Stars* (Schlesinger and Jenkins 1940) north of $-21°$, Cowley *et al.* (1969) distinguished between classical Am stars and marginal Am stars (designated as "Am:"). In an analysis of the relationship between metallicism and rotation, Abt and Moyd (1973) tentatively conclude that rotational velocity is a necessary and sufficient parameter to determine whether a star will have a normal or metallic line spectrum within certain spectral-type and age ranges. Roughly, one may say that Am stars have $v_{\rm rot} < 100$ km s^{-1} and that spectrally normal (A5–A9 IV, V) stars have $v_{\rm rot} > 100$ km s^{-1} with a few possible exceptions. In an analysis of the rotational velocities of the marginal metallic line stars, Abt (1975) refined this conclusion by stating that rotation is sufficient to determine whether a star will have a normal (A5–A9 IV, V) or abnormal (Am or Am:) spectrum, but that rotation is insufficient to determine whether a given metallic line star will be marked (Am) or marginal (Am:). In fact, all of the parameters available—temperature, age, and rotation—are insufficient to predict whether a particular metallic line star will have pronounced or mild line strength anomalies. Some other physical factor (or factors) must be operating. We suggest in this paper that pulsation is just such a factor.

II. DEFINITION OF TERMS

Because of the possibility of confusion concerning the nomenclature of the various subgroups of A stars, definitions are given here for the various terms used in this paper. Note that all of these classifications are based on some observed properties of the stars and therefore may not be homogeneous in terms of derived physical parameters or theoretical models.

Classical Am stars are stars which are classified Am according to the MK classification criteria defined by Roman, Morgan, and Eggen (1948). This usually means that the K-line type and the metal line type differ by five or more subclasses. The hydrogen line types, which are intermediate between the K-line types and the metal line types for these stars, range from A4 through F1 and are consistent with derived temperatures. The classical Am stars are metallic line stars with pronounced line strength anomalies.

Marginal Am stars, designated Am:, are metallic line stars in which there is a difference of less than five subclasses between the K-line type and the metal line type. They are Am stars in which the line strength anomalies are mild.

Early or hot Am stars are stars earlier than A4 which Conti (1965) pointed out have Am anomalies, as evidenced by the Sc II λ4246/Sr II λ4215 line ratio. So far as is known, these stars are phenomenologically the same as the classical Am stars but are not classified as classical Am because, at the surface temperature of the early A stars, the H lines are at their broad maximum, the K line is on the flat portion of the curve of growth, and the metal line strengths are weakening because of increased ionization, which makes the MK criteria insensitive to abundance anomalies.

Delta Delphini stars are stars with spectra similar to that of δ Del, that is, stars with subgiant or giant luminosity types and metal line spectra similar to those of the Am stars. In order to emphasize that similarity, Houk and Cowley (1975) have chosen to expand this classification to *Fm δ Delphini*. The δ Delphini classification is a spectroscopic classification only. It does not imply anything about the photometric behavior of a particular star.

Delta Scuti stars are Population I short-period pulsating A and F stars within 3 mag of the main sequence. The δ Scuti classification implies pulsational variability; it does not imply anything spectroscopic about a star. (See Baglin *et al.* 1973 for a complete discussion.)

III. OBSERVATIONAL DIFFERENCES BETWEEN THE Am STARS AND THE Am: STARS

Tables 1 and 2 list, respectively, the Am stars and the Am: stars classified by Cowley *et al.* (1969). The

TABLE 1

THE Am STARS

HR	b-y	m_1	c_1	β	δm_1	δc_1	ΔM_V	v sin i
178	.137	.257	.931	2.812	-.052	.136	1.09	25
250	.071	.266	.941	2.861	-.056	.054	.43	30
379								35
395	.164	.231	.747	2.816	-.026	-.055	.00	15,15
595	-.008	.205	.843	2.824	+.002	.026	.21	10
723	.076	.236	.935	2.880	-.029	.012	.09	20
895	.118	.220	.842	2.830	-.013	.013	.11	20
905	.069	.222	.967	2.883	-.015	.038	.31	40
1248	.076	.222	1.078	2.851	-.015	.210	1.68	15
1300								30,30
1329	.146	.235	.745				.00	70
1368	.197	.204	.719	2.756	-.017	.030	.24	35
1376	.180	.237	.738	2.782	-.040	.000	.00	15
1401								35
1403	.165	.211	.772	2.775	-.017	.047	.38	80
1428	.141	.236	.797	2.809	-.032	.008	.06	25
1460	.048	.216	.970	2.867	-.009	.071	.57	15
1511	.135	.230	.877	2.819	-.029	.069	.55	60
1519	.091	.252	.956	2.845	-.045	.099	.79	55
1528	.147	.225	.874	2.787	-.027	.127	1.01	15
1672	.138	.245	.840	2.813	-.040	.043	.35	10
2124								<10
2143	.139	.222	.923	2.801	-.019	.149	1.19	15
2291	.105	.264	.856	2.829	-.057	.029	.23	20
2890								35
2914	.118	.250	.904	2.840	-.042	.056	.45	55
3320								30
3354	.108	.231	.873	2.842	-.024	.022	.17	<10
3523								25,45
3572	.072	.218	1.061	2.864	-.001	.168	1.34	60
3619	.169	.233	.776	2.802	-.030	.000	.00	35
4237	.081	.219	1.011	2.849	-.011	.146	1.17	20
4535	.166	.221	.792	2.795	-.020	.029	.24	20
4646	.190	.217	.732				.12	95
4650	.151	.226	.785	2.793	-.025	.026	.21	35
4847	.191	.225	.783	2.755	-.039	.096	.77	40
5055	.067	.230	.928	2.886	-.023	-.007	.00	50
5359	.061	.206	1.005	2.874	+.001	.093	.75	15,15
5405	.128	.233	.984	2.817	-.028	.180	1.44	25
5702	.135	.218	.840	2.818	-.012	.034	.27	20
5759	.043	.210	1.004	2.891	-.003	.060	.48	40
5762	.090	.211	.981	2.865	-.004	.086	.69	15
5845	.116	.227	.868	2.859	-.020	-.016	.00	10
5887	.139	.245	.873	2.823	-.039	.058	.46	25
5892	.067	.212	.955	2.885	-.005	.022	.18	25
6129	.090	.205	.870	2.860	+.002	-.015	.00	20A
6555	.175	.222	.738	2.773	-.029	.017	.14	35
6784	.092	.226	1.077	2.864	-.019	.184	1.47	20
6811								55
6911	.088	.226	1.017	2.876	-.019	.101	.81	40
7056	.107	.224	.994	2.852	.017	.124	.99	20
7532								75
7562	.052	.202	1.018	2.879	-.005	.097	.77	10
7774								85
7839	.072	.216	1.000	2.890	.009	.058	.46	15
7849								50
7990	.186	.225	.716	2.752	.040	.035	.28	40
8293	.150	.213	.860	2.826	.006	.039	.31	30
8337								15,20
8410	.124	.237	.918	2.817	.032	.114	.91	10
8417								20,20
8578								65
8708	.168	.246	.730	2.801	.043	-.044	.00	35
8944	.166	.256	.785	2.775	.062	.060	.48	50
8970	.119	.218	.870	2.849	.010	.005	.04	50
9025	.097	.221	.955	2.840	.013	.107	.86	40

Strömgren photometric indices are taken from the compilations of Lindemann and Hauck (1973). The δm_1 and δc_1 indices were computed using the relations given by Crawford (1970), $\Delta M_v = 8\delta c_1$, $v \sin i$ for the Am stars from Abt and Moyd (1973), and $v \sin i$ for the Am: stars from Abt (1975). Stars with two rotational velocities are SB2 systems.

Figures 1 and 2 are plots of the position of the Am stars and the Am: stars, respectively, in the (β, M_v)-plane. The zero-age main sequence (ZAMS) is that given by Crawford (1970), while the dashed lines represent the observed boundaries of the instability strip near the main sequence (Baglin *et al.* 1973). The error bars represent the internal uncertainty in the M_v calibration of ± 0.3 mag. The lines of luminosity class are taken from Allen (1963). The positions of stars with $\beta > 2.88$ have been *extrapolated* from the calibration, and stars with $\beta > 2.90$ are not plotted.

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TABLE 2

THE Am: STARS

HR	b-y	m_1	c_1	β	δm_1	δc_1	ΔM_V	v sin i
290	.086	.218	.950	2.844	-.011	.095	.76	40
324	.028	.226	1.046	2.865	-.019	.151	1.21	95
418	.187	.196	.684	2.748	-.012	.010	.08	70
540	.084	.244	.886	2.856	-.057	.008	.06	60
553	.064	.211	.983	2.882	-.004	.056	.45	80
613	.055	.228	.944	2.906	-(.021)	(-.028)		20
634								30,30
39	.056	.206	.959	2.899	+(.001)	.000	.00	15
1078	.056	.228	.936	2.876	-.021	.020	.16	110
1133	.033	.179	1.090	2.883	+.028	.161	1.29	45
1138	.038	.214	1.074	2.882	-.007	.147	1.18	25,25
1139	.099	.247	.824	2.833	-.040	-.010	.00	70
1192	.077	.256	.875					55
1414	.114	.225	.912	2.823	-.019	.097	.78	105
1458	.096	.193	.948	2.834	+.014	.112	.90	55
1478	.058	.224	.992	2.887	-.017	.056	.45	60
1619								90
2108	.083	.242	.994	2.832	-.035	.162	1.30	15
2172	.066	.223	.937	2.884	-.016	.006	.05	30,30
2214	.146	.208	.920	2.799	-.005	.188	1.50	25
2372	.081	.231	.944	2.862	-.024	.055	.44	35,35
3321	.128	.194	.833	2.832	+.013	.001	.01	15
3855	.056	.210	1.004	2.879	-.003	.083	.66	100
4300	.021	.195	1.019	2.918	(+.012)	(.024)		20
4424	.092	.195	.936	2.849	+.012	.071	.57	90
4543	.160	.214	.734	2.774	-.020	.011	.09	60
4594	.170	.190	.758	2.770	+.002	.043	.34	65
4673	.087	.224	.928	2.877	-.017	.010	.08	75
4852								20
4866	.095	.230	1.032	2.842	-.022	.181	1.45	45
4917								20,20
5040	.053	.211	.974	2.892	-.004	.028	.22	20
5045	.159	.175	.875	2.770	+.017	.160	1.28	30
5749								30
5752	.046	.194	1.142	2.860	+.013	.257	2.06	30
5992								20
6250	.052	.198	1.013	2.896	(+.009)	.060	0.48	20
6611	.110	.231	1.026	2.868	-.024	.125	1.00	30,25
6876	.141	.204	.768	2.800	-.001	-.004	.00	20,20
6979								20,20
7930								25
8210	.143	.198	.785	2.806	+.006	.002	.02	65
8864								85
9022	.091	.190	1.031	2.854	+.017	.157	1.26	40

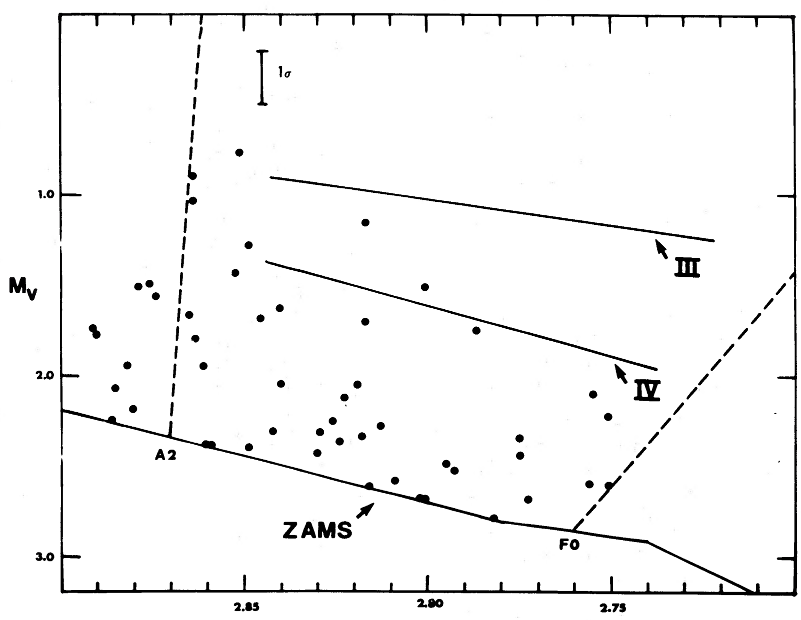

FIG. 1.—The position of the Am stars in the (β, M_v)-plane. The dashed lines represent the observed boundaries of the instability strip.

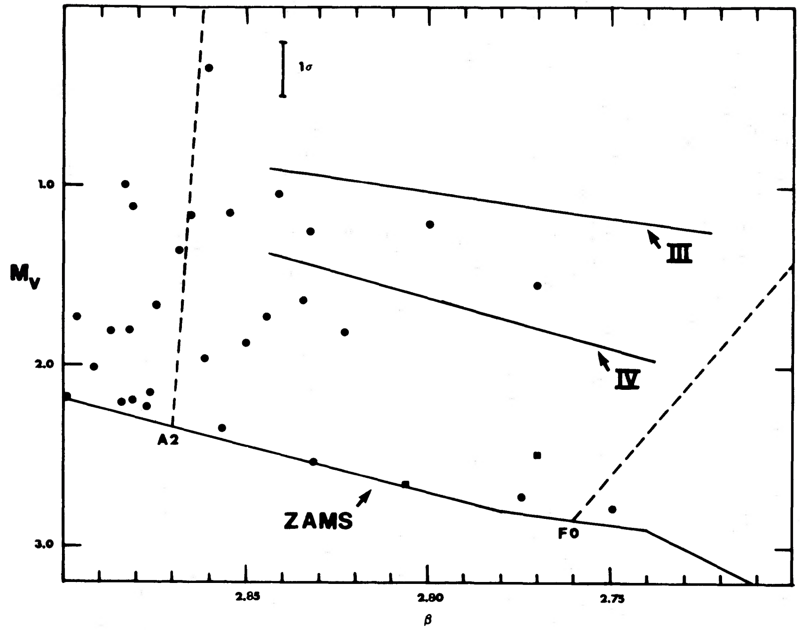

FIG. 2.—The position of the Am: stars in the (β, M_v)-plane. The dashed lines represent the observed boundaries of the instability strip. The squares represent HR 4594 and HR 8210.

For the 50 Am stars with β values listed in Table 1, $\langle\beta\rangle = 2.83 \pm 0.04$; for the 34 Am: stars listed in Table 2, $\langle\beta\rangle = 2.85 \pm 0.04$. The standard deviations here are a measure of the distribution of the stars with β and are *not* a measure of the error in $\langle\beta\rangle$. A typical error in the determination of β for a single star is $\sigma = 0.012$. If we assume a Gaussian distribution of stars with respect to β for the Am and Am: stars, then the peaks of the distributions are given by $\langle\beta\rangle = 2.83 \pm 0.002$ for the Am stars and $\langle\beta\rangle = 2.85 \pm 0.002$ for the Am: stars. The β indices imply, therefore, that, on the average, the Am: stars are hotter than the Am stars. If we use $\beta = 2.84$ (approximately corresponding to A4, the spectroscopic dividing line between the hot Am stars and the classical Am stars) as a dividing line, we see that 24/50 or 48% of the Am stars have $\beta \geq 2.84$, whereas 23/34 or 65% of the Am: stars have $\beta \geq 2.84$.

Assuming that the Am-star line strength anomalies are caused by atmospheric abundance anomalies, I suggest the following scenario. Very strong cases of Am abundance anomalies remain easily recognizable even when $\beta > 2.84$; these stars are classified as Am. But abundance anomalies that would just suffice to give rise to an Am classification in a late A star will result in a classification of Am: in an early A star. It seems reasonable, then, that many of the Am: stars are classified as marginally metallic lined not because of marginal abundance anomalies but rather because of their being *hot Am stars.*

Using Crawford's (1966) calibration of the ZAMS, Abt (1975) calculated that the Am: stars are, on the average, closer to the main sequence than are the Am stars. I have repeated that same calculation on very nearly the same set of data using Crawford's (1970) calibration of the ZAMS and $\Delta M_v = 8\delta c_1$, and I reach the opposite conclusion. Abt found for the Am stars $\langle\Delta M_v\rangle = 0.38$ mag and for the Am: stars $\langle\Delta M_v\rangle = 0.25$ mag. I derive $\langle\Delta M_v\rangle = 0.49 \pm 0.45$ mag for 52 Am stars and $\langle\Delta M_v\rangle = 0.63 \pm 0.57$ mag for 32 Am: stars. The errors quoted here are a measure of the distribution of these stars with luminosity and are not errors associated with $\langle\Delta M_v\rangle$. A typical error in the determination of c_1 for a single star is $\sigma = 0.010$. For $\Delta M_v = 8\delta c_1$, the *internal* error in the determination of ΔM_v for a single star is therefore $\sigma = 0.080$. The distribution of stars with luminosity in Figures 1 and 2 is not Gaussian. The stars are clustered toward the main sequence in such a way that the best distribution function would appear to be one-half of a Gaussian with its peak on the ZAMS. For our purposes here, however, the use of a Gaussian, which will give us some measure of the accuracy of the computed $\langle\Delta M_v\rangle$ values, results in $\langle\Delta M_v\rangle = 0.49 \pm 0.01$ mag for 52 Am stars and $\langle\Delta M_v\rangle = 0.63 \pm 0.01$ mag for 32 Am: stars. I conclude from this that, as a group, the Am: stars are significantly more evolved than are the Am stars.

The reason for the discrepancy between Abt's determination of $\langle\Delta M_v\rangle$ and mine is that the slope of the ZAMS is steeper in the 1966 calibration than in the 1970 calibration, so that the Am: stars, which are systematically hotter than the Am stars, appear to be farther from the 1970 ZAMS than from the 1966 ZAMS relative to the Am stars. While this may mean that one should not conclude anything about the evolutionary state of these stars, I prefer to think that the 1966 calibration was tentative and that the 1970 calibration is more secure. Assuming this to be true results in the following interpretation. The Am anomalies decrease as a star evolves from the main sequence to the giant region. Since the Am: stars are more evolved on the average than the Am stars, as evidenced by the calculated M_v values, then some of the Am: stars may be cases of Am stars in transition to normal-spectra giants. A star with abundance anomalies just sufficient to produce a classical Am classification on the main sequence may not need to evolve very far from the main sequence before it becomes a marginal metallic line star.

We would like to answer the following question: Why are some stars Am while others are Am:? We have just given two reasons. Some of the Am: stars may be hot Am stars, and some may be evolved Am stars. Abt (1975) further shows that the Am: stars have larger $\langle v \sin i \rangle$ than do the Am stars; since fast rotation inhibits metallicism, this also explains why some stars are Am:. But we are still left with some Am: stars which are on or near the ZAMS, have low $v \sin i$, and have temperatures within the classical Am domain. Since the number is small, one could argue that their low rotation is an aspect effect. But if we assume that this is not the case, then age, rotation, and temperature are insufficient parameters to explain why these stars have mild rather than pronounced Am anomalies. We must, therefore, search for another factor.

IV. THE DIFFUSION MODEL OF METALLICISM AND PULSATION

Following the initial calculations of Michaud (1970), Watson (1970, 1971) and Smith (1971) suggested that element diffusion could account for the anomalous abundance patterns seen in metallic line stars. Smith (1971, 1973) used extensive observational data to build a qualitative model for the Am stars in which it was suggested that element diffusion occurs in the radiative zone between the H I, He I, and He II ionization zones. This model explains the observed abundance anomalies, their temperature dependence, the low-temperature cutoff of the Am domain, and the correlation between metallicism and rotation.

Breger (1970) showed that, in general, Am stars do not pulsate; he hypothesized (Breger 1972) that, within the diffusion model for A stars, either (i) pulsation disrupts the extreme stability necessary for diffusion to occur to produce an Am star or (ii) in a star in which diffusion does occur the helium sinks out of the He II ionization zone, thus inhibiting the driving mechanism for pulsation in δ Scuti stars. Baglin (1972) and Vauclair, Vauclair, and Pamjatnikh (1974) calculate that, in a star in which diffusion occurs, helium sinks rapidly from the He II ionization zone. Vauclair (1976, 1977) has suggested a diffusion model for Am and δ Scuti stars with the following salient features: (i) Classical Am stars and δ Scuti pulsators should be mutually exclusive owing to the extinguishing of the κ mechanism by the downward diffusion of helium from the He II ionization zone. (ii) After a stable phase in which abundance anomalies develop, turbulent motions arise which restore the helium content of the He II ionization zone, so that Am stars evolve into δ Scuti pulsators. (iii) At medium rotational velocities of approximately 30–100 km s^{-1}, it should be possible for a star to exhibit both low-amplitude pulsation and mild abundance anomalies.

Kurtz *et al.* (1976) have shown that there are no known exceptions to the exclusion between the classical Am stars and the δ Scuti pulsators. Kurtz (1976) also suggested that the anomalous-abundance δ Delphini stars are evolved Am stars which exhibit both pulsation and Am-like abundance anomalies. It would seem reasonable, therefore, in light of the need for another factor to explain the Am: star and Am star distinction, and in light of Vauclair's theoretical prediction, to search the marginal metallic line stars for evidence of pulsational light variability.

I herein announce the discovery of two pulsating Am: stars, HR 4594 and HR 8210.

V. THE PULSATING MARGINAL METALLIC LINE STARS HR 4594 AND HR 8210

a) *Data Acquisition*

Observations were obtained with the University of Texas Volksphotometer attached to the McDonald Observatory 90 cm telescope. Integration times of 90 s in Strömgren y were used, and two comparison stars were observed with an observing cycle of C1VC2 except for the night of 1975 November 25, when a cycle of C1VC2VC1 was used to obtain better time

TABLE 3

STANDARD DEVIATIONS OF THE COMPARISON STARS WITH RESPECT TO THEIR MEAN

V = HR8210 C1=HR8158 C2=HR8267			V = HR4594 C1=HR4572 C2=HR4561		
UT DATE	N	σ (mag)	UT DATE	N	σ (mag)
20 OCT 75	48	0.0006	16 FEB 76	42	0.0007
23 OCT 75	32	0.0010	13 APR 76	58	0.0012
24 OCT 75	54	0.0006	16 APR 76	122	0.0011
26 OCT 75	60	0.0007	18 APR 76	70	0.0020*
27 OCT 75	58	0.0008	19 APR 76	130	0.0010
25 NOV 25	27	0.0007			

* C1 possibly variable. Only C2 used. Marginal night.

TABLE 4

PHOTOMETRY OF HR 4594

HJD 244 2000+	y (mag)	HJD 244 2000+	y (mag)	HJD 244 2000+	y (mag)
824.808	5.043	911.842	5.003	914.856	5.016
824.813	5.041	911.847	5.006	914.861	5.008
824.814	5.035	914.605	5.018	914.866	5.002
824.824	5.032	914.611	5.012	914.872	5.006
824.829	5.034	914.617	5.010	914.876	5.011
824.833	5.034	914.622	5.005	914.881	5.018
824.838	5.041	914.627	5.010	914.886	5.021
824.843	5.045	914.631	5.016	914.892	5.014
824.847	5.046	914.636	5.018	914.897	5.016
824.852	5.048	914.642	5.021	914.902	5.015
824.858	5.047	914.647	5.017	914.907	5.015
824.862	5.039	914.652	5.015	916.604	5.021
824.867	5.037	914.657	5.012	916.609	5.021
824.872	5.042	914.662	5.008	916.614	5.020
824.876	5.042	914.668	5.008	916.619	5.019
824.881	5.045	914.673	5.013	916.623	5.020
824.887	5.040	914.677	5.016	916.628	5.025
824.891	5.040	914.681	5.011	916.632	5.026
824.896	5.041	914.686	5.017	916.637	5.027
824.901	5.044	914.692	5.014	916.642	5.031
824.906	5.045	914.697	5.012	916.646	5.033
824.911	5.043	914.701	5.014	916.651	5.028
911.654	5.028	914.706	5.016	916.655	5.025
911.659	5.029	914.711	5.014	916.660	5.018
911.667	5.021	914.716	5.016	916.664	5.019
911.673	5.018	914.721	5.016	916.669	5.022
911.679	5.026	914.727	5.016	916.673	5.032
911.684	5.019	914.731	5.017	916.678	5.028
911.689	5.024	914.736	5.021	916.683	5.027
911.719	5.020	914.741	5.022	916.687	5.024
911.724	5.020	914.746	5.020	916.692	5.017
911.729	5.018	914.751	5.022	916.697	5.017
911.737	5.023	914.756	5.023	916.702	5.020
911.742	5.031	914.761	5.020	916.706	5.023
911.747	5.032	914.766	5.020	916.711	5.027
911.753	5.030	914.771	5.015	916.800	5.023
911.758	5.028	914.777	5.009	916.805	5.024
911.763	5.024	914.782	5.009	916.810	5.022
911.768	5.022	914.786	5.016	916.815	5.024
911.774	5.018	914.791	5.012	916.820	5.026
911.779	5.018	914.796	5.010	916.825	5.025
911.785	5.024	914.802	5.013	916.829	5.025
911.790	5.021	914.806	5.015	916.834	5.027
911.795	5.025	914.811	5.018	916.840	5.030
911.801	5.028	914.816	5.018	916.845	5.032
911.806	5.027	914.821	5.016	916.850	5.031
911.811	5.024	914.826	5.015	916.854	5.029
911.816	5.024	914.831	5.019	916.860	5.023
911.822	5.020	914.836	5.020	916.865	5.020
911.828	5.014	914.841	5.022	916.870	5.018
911.833	5.010	914.846	5.022	916.875	5.021
911.838	5.002	914.851	5.021	916.880	5.024
916.891	5.029	917.703	5.014	917.813	5.014
916.896	5.026	917.708	5.010	917.818	5.013
916.900	5.024	917.713	5.005	917.823	5.012
917.607	5.016	917.717	5.004	917.827	5.016
917.612	5.011	917.722	5.012	917.832	5.016
917.618	5.012	917.727	5.017	917.837	5.019
917.623	5.019	917.731	5.021	917.841	5.017
917.629	5.020	917.736	5.025	917.847	5.017
917.633	5.020	917.741	5.026	917.852	5.018
917.638	5.015	917.746	5.026	917.856	5.020
917.643	5.010	917.750	5.022	917.861	5.019
917.648	5.007	917.755	5.014	917.867	5.020
917.652	5.007	917.760	5.010	917.873	5.015
917.657	5.013	917.765	5.008	917.877	5.016
917.661	5.019	917.771	5.011	917.883	5.012
917.666	5.020	917.775	5.013	917.888	5.011
917.671	5.019	917.779	5.020	917.894	5.013
917.675	5.019	917.785	5.022	917.898	5.018
917.679	5.017	917.789	5.021	917.902	5.028
917.684	5.017	917.794	5.019	917.908	5.025
917.689	5.018	917.799	5.015	917.914	5.021
917.694	5.018	917.803	5.015	917.919	5.019
917.698	5.019	917.809	5.016	917.924	5.013

TABLE 5

PHOTOMETRY OF HR 8210

HJD 244 2700+	y (mag)	HJD 244 2700+	y (mag)	HJD 244 2700+	y (mag)
5.564	5.954	9.617	5.960	12.572	5.957
5.569	5.954	9.622	5.955	12.577	5.955
5.574	5.953	9.627	5.955	12.581	5.956
5.580	5.951	9.633	5.955	12.587	5.955
5.584	5.951	9.638	5.955	12.591	5.958
5.591	5.955	9.643	5.958	12.596	5.958
5.596	5.953	9.648	5.959	12.601	5.955
5.601	5.950	9.653	5.957	12.606	5.953
5.607	5.951	9.658	5.958	12.611	5.951
5.611	5.956	9.662	5.959	12.616	5.953
5.617	5.951	9.668	5.961	12.621	5.959
5.622	5.948	9.673	5.961	12.625	5.955
5.627	5.950	9.679	5.956	12.630	5.958
5.632	5.955	9.683	5.953	12.635	5.959
5.637	5.958	9.689	5.956	12.640	5.955
5.643	5.954	9.693	5.964	12.645	5.954
5.648	5.953	11.551	5.959	12.650	5.950
5.654	5.950	11.558	5.955	12.655	5.950
5.659	5.953	11.563	5.954	12.659	5.953
5.664	5.951	11.569	5.952	12.664	5.955
5.669	5.951	11.574	5.953	12.668	5.957
5.675	5.954	11.578	5.955	12.674	5.955
5.680	5.958	11.584	5.958	12.678	5.957
5.685	5.957	11.588	5.958	12.683	5.956
8.553	5.956	11.593	5.956	12.688	5.955
8.560	5.955	11.597	5.952	12.693	5.951
8.565	5.957	11.603	5.954	27.543	5.948
8.570	5.956	11.608	5.954	27.548	5.947
8.575	5.954	11.613	5.956	27.552	5.945
8.582	5.950	11.617	5.957	27.555	5.947
8.587	5.956	11.621	5.956	27.559	5.946
8.595	5.951	11.626	5.958	27.563	5.948
8.601	5.951	11.630	5.957	27.566	5.948
8.606	5.957	11.636	5.956	27.570	5.949
8.611	5.956	11.640	5.952	27.573	5.947
8.617	5.953	11.645	5.950	27.577	5.944
8.621	5.953	11.650	5.953	27.580	5.943
8.627	5.952	11.655	5.955	27.583	5.945
8.632	5.954	11.660	5.958	27.587	5.944
9.560	5.958	11.665	5.959	27.590	5.945
9.565	5.959	11.671	5.957	27.594	5.946
9.570	5.960	11.676	5.955	27.599	5.946
9.575	5.956	11.681	5.953	27.603	5.949
9.580	5.952	11.686	5.952	27.606	5.952
9.587	5.958	11.691	5.952	27.609	5.951
9.592	5.955	11.696	5.953	27.614	5.943
9.597	5.955	11.701	5.954	27.618	5.943
9.602	5.957	12.557	5.952	27.622	5.943
9.607	5.959	12.562	5.953	27.625	5.941
9.612	5.961	12.567	5.955	27.629	5.943
				27.633	5.949

resolution. By normalizing to the mean of the two comparisons, this technique allows the removal of very small fluctuations in sky transparency and photometric sensitivity which may occur on the best of nights and with the best of equipment. The internal standard deviation of the comparison star measurements with respect to their mean curve is typically better than 0.001 mag, so that the differential magnitude of the variable with respect to the mean of the comparisons can reasonably be assigned a standard deviation of 0.001 mag. This allows for the detection of light variability amplitudes as small as 0.01 mag with good definition of the light curve.

Table 3 lists the two variable stars, the comparison stars used, and the internal standard deviation of the comparison star magnitudes from their mean for each night of observation. Tables 4 and 5 give the reduced observations for the two variable stars. Although the internal differential magnitudes listed are generally good to 0.001 mag, the apparent magnitude scale has an estimated associated error of ± 0.05 mag. This is because no standard stars were observed, so the magnitude scale was fixed by using the V magnitudes of the comparison stars given in the *Catalogue of Bright Stars* (Hoffleit 1964).

b) *The Light Curves*

In Figures 3 and 4 the light curves for HR 4594 and HR 8210, respectively, have been plotted. The comparison stars observed on 1976 October 26 have also been plotted on the same scale at the bottom of Figure 4 to show the accuracy of the data. The solid lines are an eyeball fit to the data to facilitate viewing of the light curves. The dashed line through the third set of data in Figure 3 represents an interpretation, if one is willing to accept the 0.001 mag accuracy of the data. At the scale of these plots, 1 σ is about the size of the data points. The dashed lines which pass through no points are purely imaginary connections between

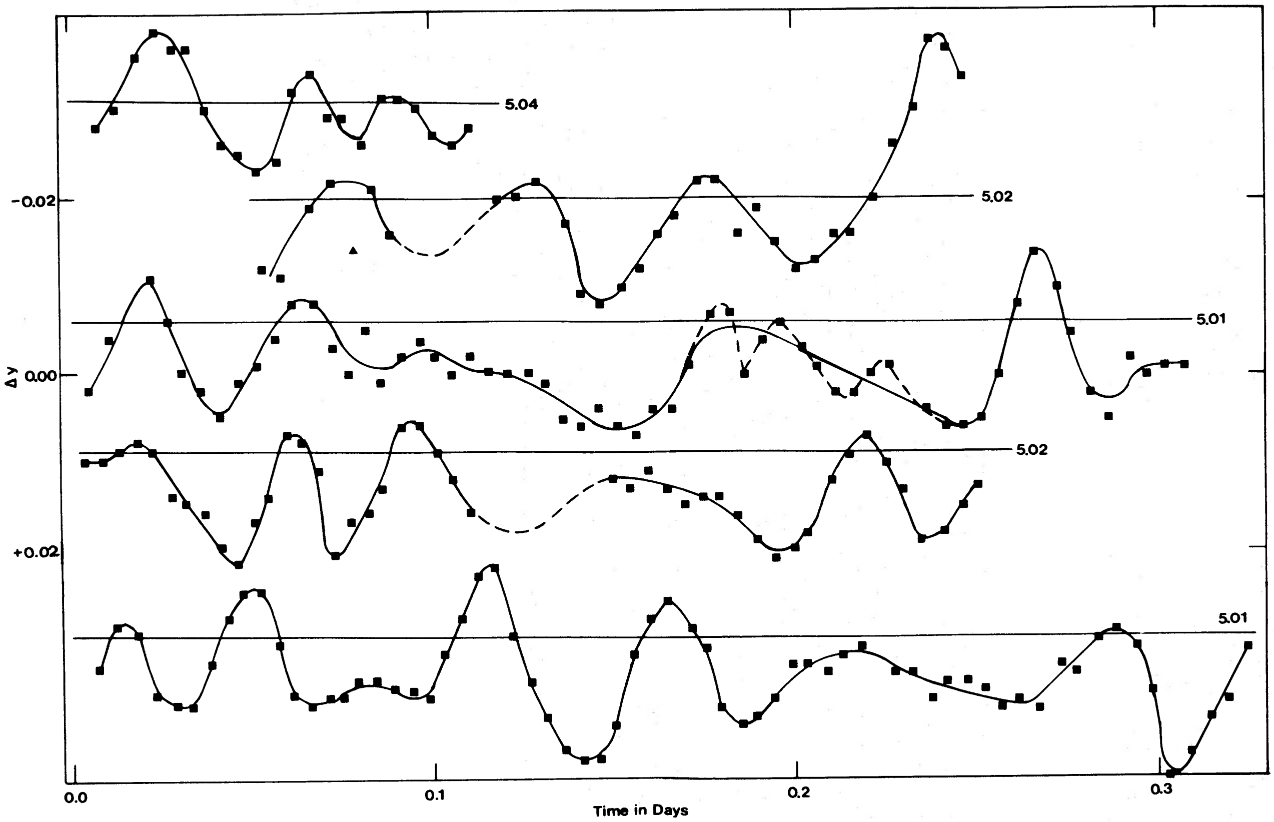

FIG. 3.—Light variations of HR 4594. The straight solid lines fix the apparent magnitude level for each night's observations. The solid curve is an eyeball fit to the data. The ordinate scale is in magnitudes.

observations which were interrupted by cloud. The straight solid lines are apparent magnitude reference lines to set the level of each night's observations. The triangle in the second data set of Figure 3 has been given zero weight in drawing the light curve, because it seems inconsistent with the other points. If one weights it equally, the light curve will have another minimum based only on that one point.

These light curves clearly establish the variability of HR 4594 and HR 8210. The nature of the variability is typical of δ Scuti–type pulsators, so we may safely assign them to that class. The amplitude of variation is of the order of 0.02 mag for HR 4594 and slightly less than 0.01 mag for HR 8210. Only a few δ Scuti stars are known to have amplitudes this small, but this is due to the difficulty of detection. Breger has shown that the incidence of pulsation increases with decreasing amplitude (cf. Baglin *et al.* 1973), as the data are consistent with the interpretation that all "constant" A2–F0 IV–V stars are variable with amplitudes less than 0.01 mag.

c) *Period Finding*

We have searched for periodicities in the light variation of HR 4594 and HR 8210 by applying a discrete Fourier transform on the data as developed by Deeming (1975). He has shown that aliasing due to the data spacing can be deduced from the information contained in the spectral window. Figures 5 and 6 present the power spectrum and spectral window for HR 8210, which is seen to have a clearly defined average frequency of 23.9 cycles per day. Although the distribution of power over frequency is quite broad, by analyzing the spectral window one can see that this is almost completely an artifact of the data spacing.

The situation for HR 4594 is much more complex. A glance at the light curves indicates that a beating phenomenon is present, an indication of multiple periodicities. The Fourier analysis bears this out. No clear-cut average period can be defined from the data. Figures 7 and 8 show that there is some power concentration at frequencies of 12.6, 15.5, 18.7, 24.5, and 29.4 cycles per day.

Using the period-luminosity-color relation for δ Scuti stars given by Breger and Bregman (1975), and the calibration of M_v in terms of $b - y$ and c_1 of Crawford (1970), we can predict a frequency for HR 8210 of 29.7 cycles per day. This derived frequency is consistent with the observed frequency within the accuracy of the relationship. We can also derive a value for the pulsation constant $Q = 0.031$ days for HR 8210, which indicates pulsation in the

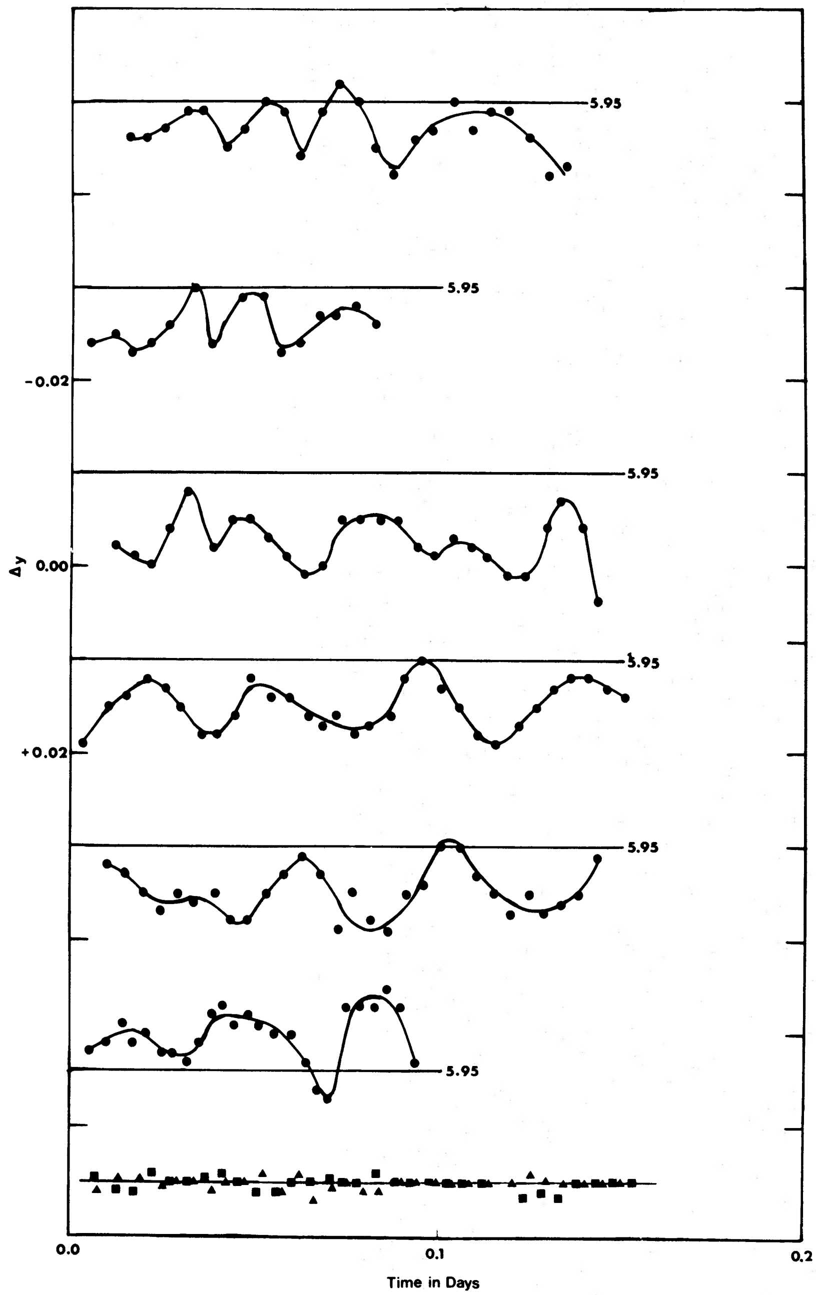

FIG. 4.—Light variations of HR 8210 with the comparison stars for 1976 October 26 plotted at the same scale. The straight solid lines fix the apparent magnitude level for each night's observations. The solid curve is an eyeball fit to the data. The ordinate scale is in magnitudes.

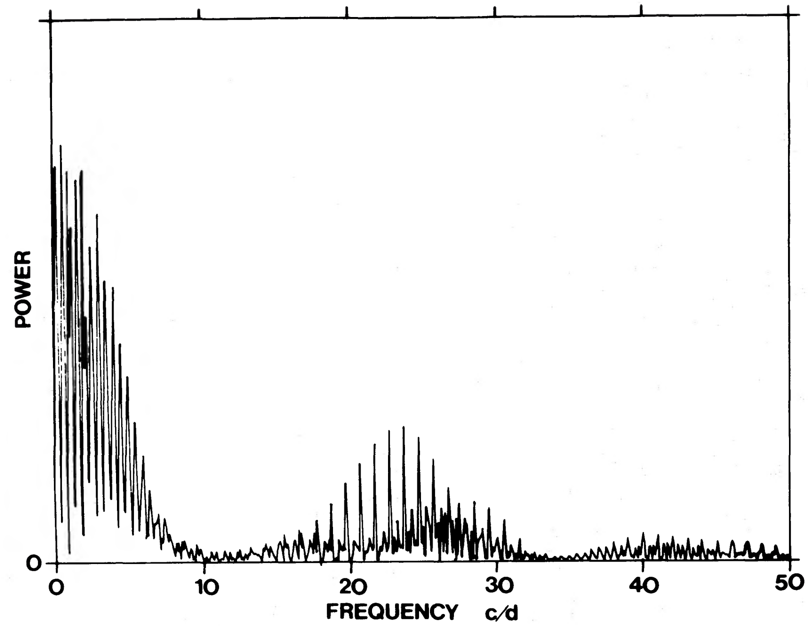

FIG. 5.—Power spectrum for HR 8210. The ordinate scale is linear.

fundamental mode under the assumption of radial pulsation.

VI. DISCUSSION

We have established that HR 4594 and HR 8210 are δ Scuti stars. Both are classified by Cowley *et al.* (1969) as Am:, and Bidelman (Abt and Bidelman 1969) says that HR 8210 is "definitely Am." Some care must be taken here, however, since occasionally one may find that discrepancies exist between spectral classification and abundance determinations for the metallic line stars.

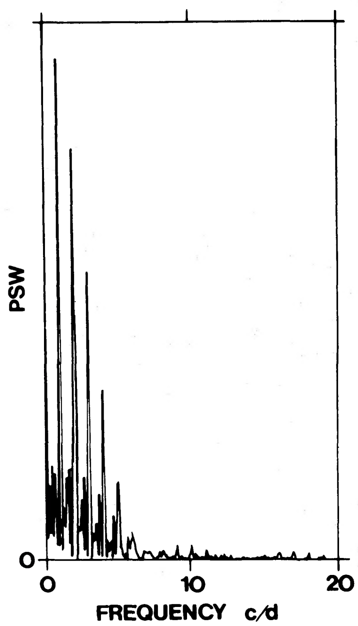

FIG. 6.—Power spectral window for HR 8210. The ordinate scale is linear.

An example of this problem is the δ Scuti variable HR 114. Cowley (1976) classifies this star as Am: and notes that previous classifications have included A7 III, Am, and F2. Abundance analyses of the star by Smith (1971) and Kurtz (1976) show it to have normal abundances. Another example is HR 2557 which is classified as δ Delphini by Cowley and Crawford (1971), is classified as A9 III by Morgan and Abt (1973), and is used as an A9 III *standard* star by Cowley (1976). An abundance analysis of this star by Kurtz (1976) is inconclusive concerning its normality. HR 3185 (ρ Pup) and HR 5017 (20 CVn) are classified as δ Delphini stars; yet abundance analyses of these stars indicate that all their metal abundances are enhanced, but metallic line abundance anomalies are not present (Kurtz 1976). All four of these stars have in common the fact that they are low $v \sin i$ giants. I suggest that this combination of slow rotation and low surface gravity gives rise to very sharp lines which can cause confusion at classification dispersion, because objects of this type are relatively rare.

HR 8210 and HR 4594 have neither of these two properties. Table 2 gives Abt's (1975) rotational velocities for both stars as $v \sin i = 65 \text{ km s}^{-1}$, and Figure 2 shows both objects to be on the main sequence. I therefore accept that the spectral classification of these two stars as Am: is good evidence that their atmospheres have marginal abundance anomalies, and discussion in this paper is based on that supposition. A quantitative knowledge of those

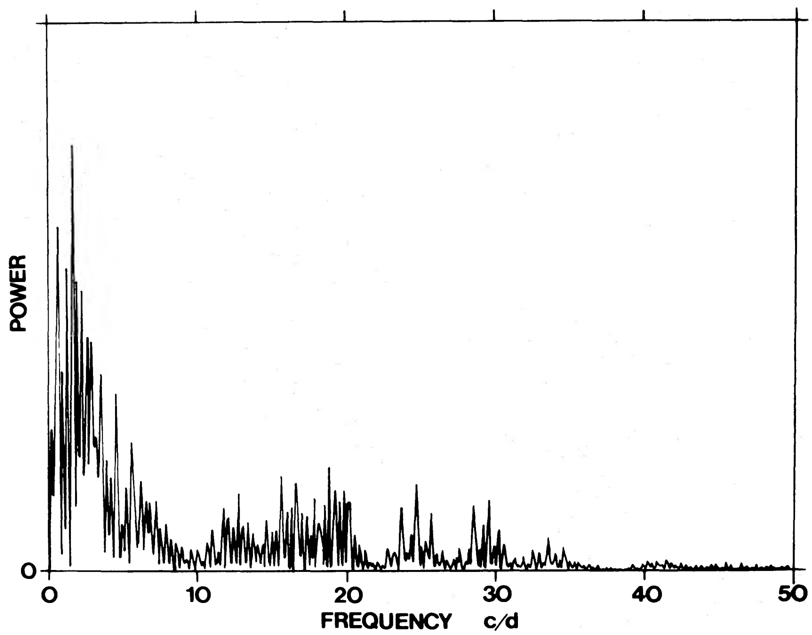

FIG. 7.—Power spectrum for HR 4594. The ordinate scale is linear.

anomalies would be most useful, but their broad lines preclude meaningful abundance analyses.

While HR 8210 is a spectroscopic binary with a period of 21.724 days, one cannot argue that it is composed of an Am star and a separate δ Scuti star, as is suggested for the pulsating Am star 32 Vir (Kurtz *et al.* 1976). Harper (1927) says that there is no definite evidence of a secondary component in this system, and I also can see no secondary spectrum on an 8.6 Å mm^{-1} coudé plate taken with the McDonald Observatory 2.1 m telescope. That HR 8210 is on the zero-age main sequence in the (β, M_v)-plane in Figure 2 indicates the secondary must be either outside the instability strip or a subdwarf. HR 4594 is not known to be binary, and no secondary spectrum is evident on an 8.6 Å mm^{-1} coudé plate. The marginal metallic line characteristics and pulsation, therefore, coexist in the same star in both of these cases.

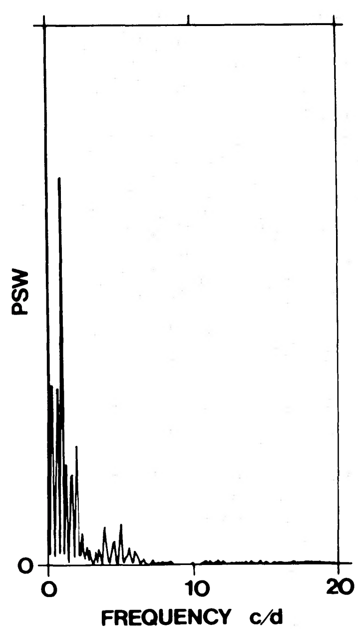

FIG. 8.—Power spectral window for HR 4594. The ordinate scale is linear.

VII. CONCLUSIONS

The observational evidence indicates that (i) classical Am stars do not pulsate (Breger 1970; Kurtz *et al.* 1976), (ii) evolved Am stars (i.e., δ Delphini stars) may exhibit metallic line anomalies and also pulsate (Kurtz 1976), and (iii) metallicism and pulsation may coexist in the same star among the Am: stars. The last conclusion is critically dependent on the previously stated assumption that the spectral classification of HR 4594 and HR 8210 as Am: is indicative of metallic line abundance anomalies. These conclusions are consistent with the diffusion hypothesis as presented by Vauclair (1976, 1977).

Within the diffusion hypothesis, pulsation is dependent on the structure of a star, which is given by its temperature and gravity (age), and on whether helium has diffused out of the He II ionization zone, which is dependent on temperature, gravity (age), and rotation. Thus pulsation is not theoretically independent of temperature, age, and rotation. Observationally, however, I suggest that, within the Am domain, knowledge of temperature, age, rotation, and whether a particular star pulsates, is sufficient to predict whether its spectrum will be normal, Am, or Am:. This begs the question of why, for two stars of apparently identical temperature, age, and rotation, one star may pulsate and the other may be constant. Perhaps small differences in these parameters beneath the present level of detection are responsible.

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