POPULATION OF THE LOWER PART OF THE INSTABILITY STRIP: DELTA SCUTI STARS AND DWARF CEPHEIDS (or AI VELORUM)

by

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ABSTRACT

In the last five years, more than 30 new δ Scuti stars have been discovered. As inferred from the statistics of dwarfs and evolved stars and also from observational bias (i.e. duration of a good sequence of photometric measurements compared to the period) most of the newly discovered stars are dwarf δ Scuti stars with periods less than 0.1 day and small amplitudes. A very luminous one has been detected around $M_V = 0$.

The problem of period determination has not yet been completely settled and the stars can still be divided into two groups: stars with apparently no stable period (almost all the dwarfs and some low amplitude giants) and stars with stable combination of period and repetitive light curve (giants with large amplitude and/or binaries). The last class resemble the AI Velorum in this respect.

Some properties of the atmospheric variations in δ Scuti stars are emphasized. The amplitude and the shape of both light curves and radial velocity curves are small and rapidly variable in the case of dwarf δ Scuti stars; for the evolved stars the situation is more complex. Rapid rotators have small amplitudes while slow rotators have larger ones. Moreover the shapes of the light curves are more regular. Recent work on spectrographic data points out some bumps in the radial velocity curves and in the core of strong line profiles. These phenomena appear qualitatively very similar to those observed in Cepheids and described by Karp in his hydrodynamical model of a 10 day Cepheid.

The relation between variables and non-variables, and also the results on abundances in the atmospheres of these stars has already given some insight of the hydrodynamics of their envelopes. However, if diffusion theory explains qualitatively the abundances anomalies of the Am stars, a quantitative agreement has not been reached yet. This microscopic diffusion prevents the vibrational instability when it is at work. The mechanism which prevents diffusion is still associated to rotation, but no complete hydrodynamical model exists.

The coexistence of abundances anomalies and variability among giants has been strongly confirmed, and on the main sequence two variables seem to be mild Am. This fact poses a new problem to the diffusion theory, as it is difficult to understand how diffusion could be strong enough to produce abundances anomalies and at the same time turbulence strong enough to mix the helium. Attempts have been made to relate the variability to the hydrogen ionization zone in an envelope deprived from helium. But the comparison with observations is not very good. A better description of the hydrodynamics in these envelopes is badly needed.

The AI Velorum stars are treated separately because the main problem under discussion is the question of their population. This group has been defined by their pulsation characteristics: short period, larger amplitude and regularity of the light curves. Contrary to RR Lyrae or δ Scuti stars their evolutionary status is not known. The existence of RR Lyrae stars in globular cluster and of δ Scuti stars in open clusters allow to infer that RR Lyrae belong to population II or intermediate population I and that the δ Scuti are typical population I stars. In the case of the AI Velorum stars the problem is less clear. Observationally the values of the metal content, period and velocities calculated from proper motions show a large dispersion. From pulsational models it is possible to obtain the observed period with high masses (2 $M_\odot$) and normal metal content, but also with low metal content and low mass (0.5 $M_\odot$). So that we conjecture that the AI Velorum stars do not form a homogeneous group from the population point of view.

I. Introduction

In the population of the lower part of the instability strip (from the main sequence up to $M_V = 0$) one can distinguish different groups: δ Scuti stars (as defined in Baglin et al. (1973)), metallic line stars (as defined for example by Conti (1970)), and AI Velorum stars for which a definition is given in Section V. Since Breger (1969) the normal A stars are considered as low amplitude pulsators; i.e., δ Scuti stars. The main properties of δ Scuti and AI Velorum stars have been reviewed by Baglin et al. (1973) and then complemented by review papers of Fitch (1976), Petersen (1976), and Baglin (1976) at the IAU Colloquium 29 in Budapest. The properties of AI Velorum stars have been more recently studied and discussed extensively by Breger (1976). The extension of the Am domain and the variation of the Am character is being extensively looked at (see for example Burkhart (1978)).

We do not want here to give an extended review of all the works which have been done on the subject but rather emphasize the problems raised by these stars. We first review the newly discovered variables (Section II), then discuss new results on the atmospheric properties of their pulsation (Section III). The coexistence of variables and non-variables related to abundances anomalies is discussed. Emphasis is made on the questions raised concerning the physical processes at work in the envelopes of these stars (Section IV). Recent works on the properties of AI Velorum stars confirm the fact that the lower part of the instability strip probably contains variables of different populations, and that the definition of the two groups, AI Velorum and δ Scuti, do not represent this difference (Section V).

II. General Statistical Properties: Discovery of New Variables

A. Discovery of New Variables

During the last five year some thirty new δ Scuti variables have been detected. Most of them are of luminosity classes V and IV with short periods between 0.05 day and 0.1 day and small amplitude, i.e., dwarf δ Scuti stars.

They are listed in Table I, which can be considered as an addition to the catalogue of Baglin et al. (1973). It has to be noticed that the mean duration of excellent sequences of photometric measurements favor evidently the discovery of stars with periods less than 0.1 day. γ Bootis, which our group has recently classified as a δ Scuti variable, is a good example of the difficulties to observe stars with periods longer than 0.2 day. In addition the dwarfs are the most numerous due to their longer evolutionary time scale. However, the discovery of HR 2557 by Kurtz (1977) extends the δ Scuti domain to very high luminosities ($M_V \simeq 0$). These results definitely confirm that the δ Scuti and AI Velorum domains overlap (see Section V).

B. Periods

The problems of the stability of the variations in δ Scuti stars has not yet been solved. The complexity of the light curves needs long photometric sequences to make a serios period analysis. Nevertheless, from the few stars studied up to now, some conclusions can be drawn.

It seems that the CC And is the only star in which tidal modulation is responsible of the complexity of the light curve (Fitch, 1967). In the case of 14 Aur (Morguleff et al., 1976; Fitch, 1976) or Y Cam (Broglia and Marin, 1974) for instance, the binary nature does not appear in the mixture of periods. Except the particular case of CC And, all the objects which have been studied extensively up to now can be separated into two groups:

- The evolved large amplitude δ Scuti stars seem to have several stable periods and repetitive light curves as for example 14 Aur (Morguleff et al., 1976) or 1 Mon (Shobbrook et al., 1974). This stability in the period spectrum seems to exist also in small amplitude giants as 38 Cnc for instance (Guerrero, 1978) or 4 CVn (Shaw, 1977).
- The dwarf δ Scuti stars, which have generally (but not always) small amplitude of variations, non stable periodicities and non repetitive

light curves, as for instance, Θ Tuc (Stobie et al., 1976), HR 4684 (Guerrero, 1978), HR 8006 (Le Contel et al., 1974), or HR 812 (Fesen, 1973). However, this "classification" is only tentative and needs more studies to be confirmed.

III. Properties of the Atmospheric Variations in Delta Scuti Stars

The amplitudes of radial velocity curves are low and generally variable (as in photometry), generally lower than 40 km/s. The correlation between large amplitudes and low projected rotational velocity (V_R sin i) which has been claimed by different authors has still to be confirmed.

Light and radial velocity curves are roughly in opposition: Breger et al. (1976) studying seven stars showed that minimum velocity and maximum light are shifted by 0.09 period which means that the phase lag is less than in Cepheids. They proposed that the reason for this is the reduced H-ionization zone of δ Scuti stars which is located very high in the atmosphere of these stars. However, in Cepheids, when a secondary bump is present in both light and radial velocity curves, Stobie (1976) pointed out that the two curves are not mirror images so that the observed phase lag is not exactly 90°. The observed shift in δ Scuti stars may be due to the same reason, at least for evolved ones (Auvergne et al., 1978, on γ Boo; Valtier et al., 1978b, on HR 432 and HR 515) in which bumps are present at the minimum and maximum of the radial velocity curves. In the case of HR 515 simultaneous observations of the continuum allow us to see that a bump is also present around maximum light (fig. 1). These irregularities are related to line profile variations of the strong lines (Balmer lines and Ca II K line). In particular a line splitting of the K line is observed at the end of the radial velocity bump. Dravins et al. (1977) have observed the same phenomenon in ρ Pup.

Such perturbations of light and radial velocity curves associated with line profile splitting are similar to what is observed in Cepheids. The same kind of phenomena have been obtained by Karp (1975) in his hydrodynamical models of a 12 day Cepheid: the critical period of the atmosphere and the period of the envelope are very similar so that resonance phenomena may appear. As the envelope is still expanding the atmosphere starts to slow down. A pressure wave is generated which propagates both inward and outward and heats the gas. The observed line splitting could be produced by this temperature uprising when it is strong enough at small optical depths. However we have to explain how it is possible to observe such splittings (with a characteristic length of 60 km/s) in the core of lines in such rapid rotators as γ Boo (145 km/s) or HR 515 (200 km/s). In the case of a velocity field, it has to be concentrated on some parts of the disk. A possibility could be looked for with non radial oscillations.

IV. Properties of the Envelopes: Coexistence of Variables and Non Variables

We will discuss in this section the atmospheric abundances of the variables and of the non variables in the same domain. These abundances are built at the bottom of the convective zone, down in the envelope and will give information on the hydrodynamical behaviour of these deep layers.

A. Observational Results

1. On the main sequence the exclusion metallicism-pulsation is generally confirmed. Since the discussion by Baglin (1976), 32 Vir has been recognized as a binary star with one Am and one δ Scuti star (Kurtz et al., 1976). However, two stars on the main sequence HR 4594 and HR 8210 have been discovered as variable by Kurtz (1978); they are classified as mild Am. The classification mild Am is dubious - for example 28 Andr has been classified mild Am with the same spectral type as HR 8210 but the detailed analysis has shown that it has normal abundances. So, as no detailed analysis of abundances is available for these two stars one has to be careful before claiming the coexistence of anomalies and variablity on the

main sequence. In addition it is not completely settled that no companion exists (as in the case of 32 Vir), as the stars rotate quite fast.

2. Outside the main sequence the situation is more complicated.

a) The evolution of the Am character towards the giant domain has been studies in more detail. Smith has defined abundances of "evolved Am" from an analysis of several stars lying one or two magnitudes above the main sequence (HR 1103, 1248, 3752, 6559, 7653 cited by Kurtz, 1976). But Burkhart (1978) analysed the hot evolved Am 22 Boo and α Cnc and found that they look like classical Am stars. Kurtz (1976) studied stars classified as δ Del (Bidelman, 1965) which are generally quite cool and found that some of them have abundance anomalies compariable to the "evolved Am" as defined by Smith though some of them do not show any abundance anomalies.

So that the evolution of the abundance anomalies toward the giants seem to present important variations from one star to another and no clear correlation with either temperature or gravity has been established (Table 2 and figure 2).

b) The giants variables have peculiar pulsation characteristics (See section III).

Some abundances analyses are available. Kurtz (1976) obtained a homogeneous set of results on seven known variables. In some cases they are comparable to the Smith "evolved Am" while in other cases [Fe/H] is enhanced and the relative abundances with respect to iron are normal. However, the coexistence of variability and abundance anomalies can be considered as proven. Up to now, no statistics can be made because only a few stars have been tested. Some work is in progress in that domain, and in particular testing variability of giant Am is badly needed.

B. Theoretical Interpretation

These properties -variability and abundance anomalies - give us some insight on the structure of the envelope of these stars down to the bottom of their convective envelope.

1. Variability is due - at least on the main sequence - to the helium ionization zone and is present only when the concentration of helium is larger than 0.15 More stability analysis have been done recently which defines the blue border of the strip for normal population I composition (Percy, 1977; Valtier et al., 1978a; Stellingwerf, 1978). As for Cepheids the theoretical blue border is too red (figure 3). Fundamental and first harmonic are unstable almost for the same conditions, depending a little bit of the outside boundary conditions.

2. Abundance anomalies are qualitatively explained by the microscopic diffusion in stable medium (Michaud et al., 1976). But a quantitative agreement is not yet reached. Vauclair et al. (1978) propose to add some turbulent diffusion due either to overshooting or shear instability due to meridional circulation which would prevent the concentration to become too high. They tried to estimate an "ad hoc" coefficient and show that the observed abundances of some of the elements can well be explained but that the rare earths abundances are still too low by a large amount. Microscopic diffusion deprives also the envelope from helium. Within 10^6 years no helium is left down to 0.1 R_* in a stable envelope of an A star. Turbulent diffusion as proposed by Vauclair et al. (1978) is not large enought to prevent this sorting.

3. Exclusion between metallicism and pulsation

As it is the same mechanism which is responsible for abundance anomalies and vibrational stability the exclusion between metallicism and pulsation can be understood. In a variable, it does not take place because some mixing process is at work which prevents diffusion. As from observations one knows that statistically slow rotators are Am and fast rotators are variables, the mechanism which prevents diffusion is probably due to rotation. Several works have proposed the shear flow due to the meridional circulation as the agent of mixing (Baglin, 1972; Vauclair, 1976, 1977) but no satisfactory picture exists now, and the crude treatment of the hydrodynamical behaviour of these envelopes has to be improved. As we have seen the coexistence of metallicism and pulsation is well established for giants and could also be present among some dwarfs. Helium is so easily sorted that it is difficult to understand how an envelope could be quiet enough to allow diffusion to produce abundance anomalies and turbulent enough to prevent the sorting of helium.

Valtier et al. (1978a) propose that the variability is due to another vibrational instability seated in the hydrogen ionization zone, which grows when the gravity decreases instead of the helium ionization zone. They have computed the instability of such hydrogen envelope models and can find an instability but quite marginal and in a very small domain (figure 3). A lot of work has to be done on this intriguing question which will bring some insight on the hydrodynamic of the envelopes.

V. Are AI Velorum and δ Scuti Stars the Same Group of Objects?

From the pulsational properties (period less than 0.2 d, amplitude greater than 0.3 m and regularity of light curves) and AI Velorum stars belong to a well defined group. They are distinct from δ Scuti stars by their amplitude and the shape of their light curves, and from RR Lyrae stars by their period. There are some objects for which the classification is not so clear: for instance DE Lac (P_o = 0.254 d) or δ Sct itself (amplitude = 0.29 m), but the existence of these three groups defined with pulsational characteristics is not doubtful. We have listed in Table 3 the main characteristics of the best known AI Velorum stars. However, since several years the question has been raised of the physical nature of the AI Velorum stars which occupy approximately the same domain of the HR diagram as the δ Sct stars. Detailed reviews of the subject have been given by Fitch (1976) and Petersen (1976) and also by Breger (1976). Breger, considering that only a detailed study of individual objects would bring some light on the subject, observed AD CMi (Breger, 1975), VX Hydr (Breger, 1977a) and AI Velorum (Breger, 1977b). He found that metallic index and the mean gravity indicate that these stars are high masses population I objects. Previously some stars like AI Vel were considered to belong to population II stars on the basis of very imprecise parallaxes or observed period ratios. Petersen (1976) has shown that in the domain covered by the dwarf cepheids the P_1/P_o ratio is not a good indicator of the mass and the metal content. But Stellingwerf (1978) indicates that the same P_1/P_o ratio can be obtained for models of low mass $M = 0.4M_\odot$ and low metal content $Z = .005$, and for models fo high mass $M = 3\text{-}4\ M_\odot$ and high metal content $Z = 0.02$. He also emphasized the difficulty of determining the mass, as many modes are unstable. Using a higher mass leads to accepting a higher mode. The ambiguity could be restricted only if the luminosity was known, which implies the knowledge of the parallax!

A new dwarf Cepheid has been discovered with a particularly short period (0.039 d) by Berg and Duthie (1977) and spectra have been obtained by McNamara and Feltz (1978). These authors conclude that the star (GD 428), though metal poor, is evolving off a metal poor main sequence and is still in its hydrogen shell burning stage.

From the period luminosity-color relation Breger and Bregman (1975) found SX Phe above the population I locus in the absolute magnitude-period diagram. As the longer period population II stars are also above the population I Cepheids they conclude that SX Phe probably belongs to the population II.

At the present time it seems confirmed that the AI Velorum stars, as defined by their pulsational properties do not form a homogeneous group. Most of them are the same kind of objects as δ Scuti stars. But some stars as SX Phe or GD 428 seem to be definitely metal poor, and some others like DY Peg or CY Aqr have high log g and intermediate δm_1 (see table 3). If we accept the idea that most of the AI Velorum stars are not different from

δ Scuti stars, it is necessary to explain why the amplitude of these stars is so large and the light curve so regular. Evidently the problem of explaining the amplitudes leads to a non linear hydrodynamical treatment of the pulsation. In the case of AI Velorum stars the growth rate is so small that different techniques like non-linear relaxation (Stellingwerf, 1974) are needed.

By the presence of two main excited modes with quite large amplitude they look like the double mode Cepheids. Stellingwerf (1975) has predicted a double mode pulsation for one of his models representing a dwarf Cepheid. However other investigators like Hodson and Cox (1976) have failed to reproduce the results. Simon (1978) proposes that these stable double mode pulsations can be explained by a resonance. It explains the small range of P_1/P_o, but the population I hypothesis has to be excluded.

From this short review it appears that both from the observational and theoretical points of view the situation is still confused.

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Table 1

New δ Scuti variables

HD	HR	S T	Name	Periods	Amplitudes	V	M_v	Log T_{eff}	Ref
4490	214	A 5	59 Psc	0.104	0.04	6.01	1.19	3.88	1
4818	238	F 6		0.136	0.025	6.39	2.29	3.87	2
4849	239	F		0.055	0.15	6.47			3
11285		F 0		0.08	0.02	6.8			18
14940		F 0		0.21	0.005	6.6			18
15165-4		A 3		0.100	0.07	6.71			19
28319	1412	A 7 III	78 Tau	0.07	0.03	3.41			9
30020	1505	F 2 III	55 Eri			6.75	2.23	3.85	11
50420	2557	F 0				5.98	0.	3.87	16
71496	3329	A 5	28 Cnc	0.096	0.02	6.05	1.21	3.89	13
71935	3350	F 3		0.07		5.10	1.05	3.87	11
75747	3524	A 5	RS Cha	0.08		6.04			4
74439	3662	A 5 V	18 UMa	0.125	0.03	4.82	2.07	3.91	13
85040	3889	A 8	20 Leo	0.082	0.04	5.92	1.54	3.89	8
104513	4594	A m	67 UMa	0.08		5.00	2.48	3.88	15
108506	4746	A 8 n		0.05		6.23	1.59	3.81	11
110377	4824	A 5	27 Vir	0.05	0.02	6.30	1.83	3.89	7
127986	5441	F 5		0.13	0.02	6.38	2.94	3.79	5
153747		A 1		0.05	0.02	7.41			6
199603	8024	A 3		0.12	0.1	6.02	1.52	3.89	10
201707	8102	F 0		0.097	0.1	6.48	1.27	3.88	10^{a}_{b}
204188	8210	A m		0.04		6.03	2.83	3.90	15
215874	8676	F 0	70 Aqr	0.086	0.025	6.15	1.35	3.89	3
223781	9039	A 3	82 Peg	0.06	0.005	5.29	1.36	3.91	14

Table 1
(end)

HD	HR	S T	Name	Periods	Amplitudes	V	M_v	Log T_{eff}	Ref
		A 7 V	Y Cam	0.063	0.04	10.45			12
BD + 48°894		F 0 IV		0.037	0.012	9.14	2.8		17
BD + 48°905		A 8 V		0.03	0.014	8.98	2.8		17
BD + 47°842		A 6 Vn		0.08	0.022	8.78	2.4		17

M_v and log T_{eff} from Dunley Observatory Report.
V and Sp type from H.R. Catalogue, except for the three last stars see 17.

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Table 2

Abundances relative to the Sun of a "classical Am" 63 Tau, 3 evolved Am (15 Vul, 22 Boo and α Cnc) and two δ Delphini stars (δ Del and ρ Pup).

	63 Tau	15 Vul	22 Boo	α Cnc	δ Del	ρ Pup
log Te	7650	7650	7750	8400	7320	7100
log g	4.4	3.5	3.5	3.8	3.25	3.25
Ca	-0.7	-0.3	-0.4		-0.08	.6
Sc	-0.45	-0.35	-0.5	-0.8	-0.40	.2
Cr	1	-0.1	-0.1	-0.3	-0.20	.1
Mn	0.5	-0.3	0		+0.06	.5
Fe	0.8	0	0.1	0	0	.54
Ni	1.2	0.4	0.7		0	.7
Zr	0.5	0.65	0.8		0.3	.6
Ba	15				0.7	.2
Y		1.1	0.8	1.1		
Eu	1.6	0.55	1.2	1.1	0.8	1.3

(1) 63 Tau is from Provost et al. (1969).

(1) 15 Vul is from Faraggia et al. (1973).

(2) 22 Boo and α Cnc are from Burkhart (1978).

(3) δ Del and ρ Pup are from Kurtz (1976).

Table 3

Characteristics of the best known A I Velorum Stars.

Star	P_o	P_1	ΔV	T_{eff}	<log g>	$<m_1>$	M_v π,T / c_1	δm_1
SS Psc	0.288		0.43	7300 °K	3.29	0.178	0.7/0.3	+ 0.01
BS Aqr	0.198		0.51	7200	3.60	0.177	0.8/1.0	+ 0.002
VZ Cnc	0.178	0.143	0.29	7100	3.62	0.181	1.3/1.1	− 0.004
DE Lac	0.254		0.31	6960	3.57	0.180		
SX Phe	0.055	0.042	0.51	7850	4.20	0.135	2.9	0.135
CY Aqr	0.061	0.045	0.73	7930	4.13	0.146	2.8	0.059
AE Uma	0.086	0.66						
RV Ari	0.093	0.072	0.7					
DP Peq	0.109	0.084	0.4					
AI Vel	0.111	0.086	0.67	7620	3.98	0.176	1.1/1.7	0.018
V703 Leo	0.149	0.115	0.50					
VX Hya	0.223	0.173	0.1-0.68	6940-7040	3.49-3.46	0.180	0.1/1.1	+ 0.006
AD Cnc	0.123		0.32	7580	3.94	0.181	0.9/1.6	0.009
GD 428	0.039			8050	4.18	0.08	4.4	0.125
DY Peg	0.073		0.54	7800	4.0	0.141	2.7	0.062
EH Lib	0.088		0.50	7930	4.12	0.175	1.3	0.028
YZ Boo	0.104		0.40	7650	3.97	0.175	1.8/1.1	0.021
SZ Lyn	0.120		0.48	7540	3.88	0.189	1.3/1.6	0.001
RS Gru	0.147		0.56	7600	3.83	0.158	0.7/1.3	0.035
DY Her	0.148			7130	3.66	0.188	1.8/1.3	− 0.012