PART 4

δ SCUTI STARS

STARS OF δ SCUTI-TYPE IN STELLAR CLUSTERS

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Abstract. The frontier of our knowledge of δ Scuti variables is reviewed with emphasis on the following topics: (1) pulsation in specific clusters; (2) rotation and pulsation in different clusters; (3) metallicism and pulsation; and (4) periods and pulsation modes of δ Scuti stars.

1. Pulsation in Specific Clusters

During the last ten years, δ Scuti variables have been detected in several galactic clusters. Since a δ Scuti star may mean different things to different people, one should give a definition of the δ Scuti type of variability. My personal working definition is the following: A δ Scuti star is a pulsating variable of spectral type *A* or *F* with a period less than 0.25 days and a mass of 1.3 solar masses or larger. In practice this means a Population I star contracting towards the main sequence, on the main sequence or moving towards the giant region for the first time. This definition incorporates all certain variables found so far and excludes any short-period extremely undermassive Dwarf Cepheids, some of which may be below the main sequence. A typical δ Scuti has a near-regular period of one hour and an amplitude of 0.02 mag.

To me it has always been as interesting to determine which stars do not pulsate, as it has been to find more variables. The results of several variability surveys are shown in the first four diagrams, where the clusters are grouped according to age. The excellent work on NGC 7789 was made by Danziger (1971). Jakisch (1972) in East Germany provided some confirmation about the three stars in Praesepe with marginal variability (he also found them to be variable), and two variables in the Hyades cluster were taken from Millis' thesis. The remaining stars were observed by me mainly at Kitt Peak National Observatory and McDonald (Breger, 1972, and unpublished). These diagrams also show the observational borders of the δ Scuti instability strip. These observational borders bracket the presently known variables, but exclude a few stars with presently less certain existence, period and nature of their variability. The observational borders, which intersect the zero-age main sequence at $\log T_{\text{eff}} = 3.95$ and 3.88, are a function of the helium abundance of the stars. Calculations of the Blue Edge made by Cox *et al.*, (1973) indicate good agreement between theory and observations for the (reasonable) helium abundance of $Y \sim 0.3$.

We can conclude that pulsation in open clusters is very common and apparently not dependent on age, as long as sufficient stars are situated in the instability strip. Two pre-main-sequence variables were found in NGC 2264. While their membership really needs to be confirmed, they are very probable members. This places the observed lower age cutoff for δ Scuti pulsation near 10^6 yr. On the other hand, the variable in NGC 7789 puts the upper age cutoff beyond 10^9 yr.

Sherwood and Plaut (eds.), Variable Stars and Stellar Evolution, 231–241. *All Rights Reserved.*

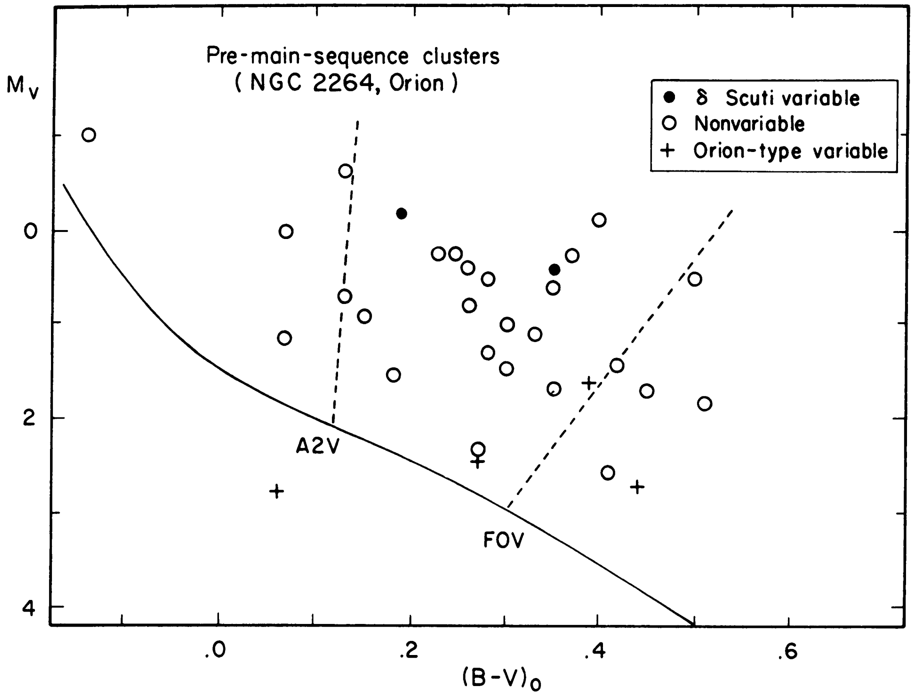

Fig. 1. Position of variable and non-variable stars in the H-R diagram.

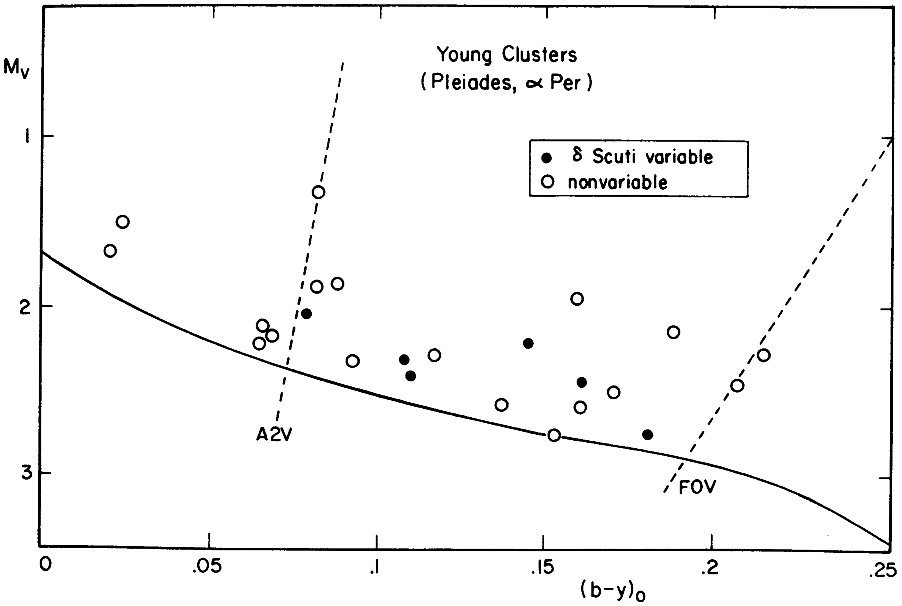

Fig. 2. Position of variable and non-variable stars in the H-R diagram.

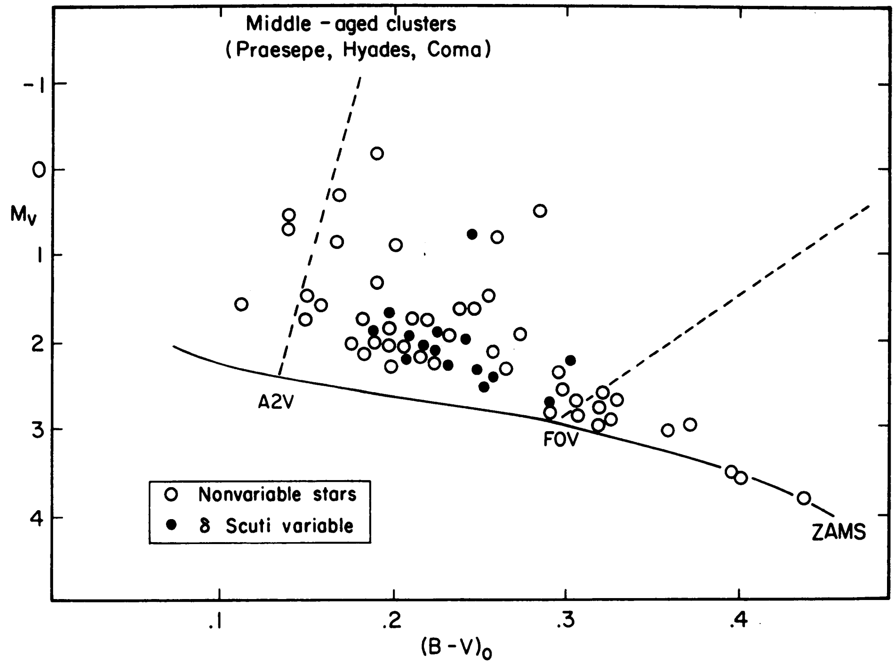

Fig. 3. Position of variable and non-variable stars in the H-R diagram.

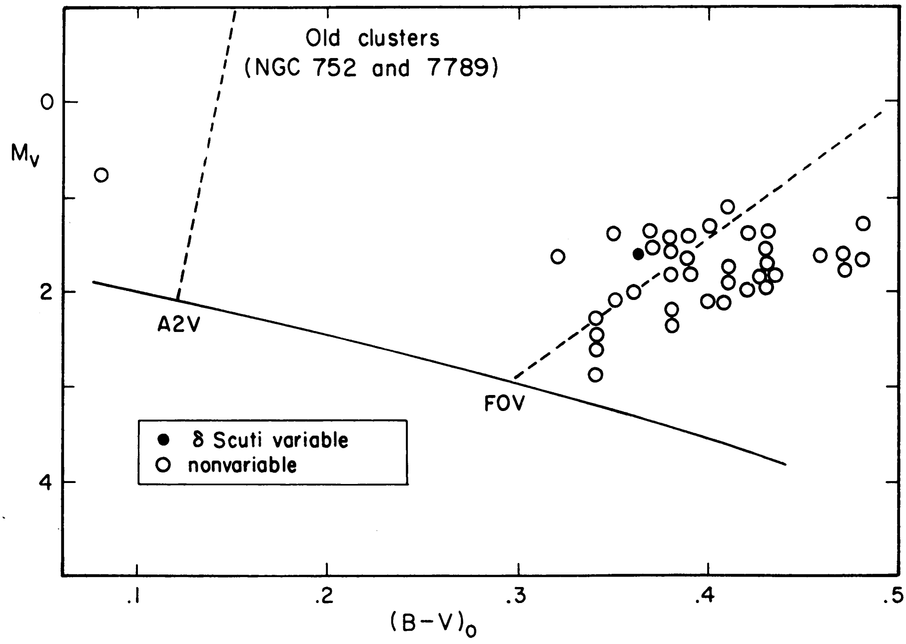

Fig. 4. Position of variable and non-variable stars in the H-R diagram.

Do the chances of a star becoming a δ Scuti variable depend on age or abundance? To some extent, evolutionary status can be important. After all, the 'large-amplitude' variables are almost all sharp-lined giants. Before one can make an actual comparison between the incidence of variability in different clusters, an important adjustment needs to be made. Most δ Scuti variables have very small amplitudes, so that a very accurate survey detects considerably more variables. The size of the 'constancy' of the non-variable stars in these clusters allows us to estimate the completeness factor. This was combined with the histogram of the amplitudes of known variables. For the faint clusters this adjustment increased the number of expected variables threefold. The results are shown in Table I, where it can be seen that the adjusted incidence of variability (larger than 0.01 mag.) is rather similar from age group to age group. It is presently not possible to conclude more than that.

TABLE I

Incidence of pulsation in open clusters (Inside instability strip only)

Type of Cluster	Number of stars		Fraction variable	
	δ Scuti	No detection	Observed	Adjusted
Pre-main-sequence ($\sim 2 \times 10^6$ yr)	2	17	0.1	0.3
Young ($\sim 10^8$ yr)	6	11	0.35	0.35
Middle-age ($\sim 10^9$ yr)	15	35	0.30	0.32
Old ($\sim 5 \times 10^9$–10^{10} y))	1	9	0.1	0.3

It may appear surprising that the number of variables found in the clusters is so high. The incidence of variability among the field stars certainly appears to be lower. In our opinion the main reason for this apparent difference lies in the fact that the proximity of sufficient comparison stars in the clusters allows a very high precision of measurement, generally of the order of 0.001 mag, a precision not always attainable amongst the field stars.

2. Rotation and Pulsation in Different Clusters

The δ Scuti instability strip is filled with pulsating as well as non-variable stars. Many of these non-variable stars may in fact be pulsators with very small amplitudes below the limit of detectability. Are there any differences between the variables and non-variables? The first criterion which comes to mind is chemical abundance. Yet, the main sequence stars in each cluster are believed to have similar chemical abundances and we find both variables and non-variables in each cluster. So we have to look elsewhere for an explanation of non-variability.

The observational data show that the rate of rotation of a star is very important in predicting whether or not a star will pulsate. Table II summarizes the data, which were collected from our papers and the work by Danziger and Faber (1972). We note that:

(i) Among giants high rotation inhibits pulsation. Consequently the (longer-period) δ Scuti variables have a lower rotational velocity, $v \sin i$, than the non-variable stars of similar luminosities. Also, slow rotation is a necessary condition for large amplitudes.

TABLE II

Relation between pulsation and rotation

Stars (Clusters)	No. of Stars	Average $v \sin i$ (km s^{-1}) Variable stars	Constant stars	Significance of difference (t-Test)
Giants	37	77 ± 13	124 ± 10	0.99
Dwarfs Praesepe, Hyades and Coma	30	149 ± 9	81 ± 14	1.00
Pleiades	14	87 ± 28	122 ± 13	0.80

(ii) On the main sequence, however, pulsation and fast rotation can co-exist. In fact, the average main sequence δ Scuti variable rotates faster than the non-variable star. We regard this difference now to be statistically very significant with a chance occurrence of less than 0.1%. The reason for this complete reversal probably lies in the fact that the classical metallic-line A stars, which are slow rotators and are on or near the main sequence, tend not to pulsate (see Section 3). This then would make most sharp-lined main-sequence A stars non-variable.

(iii) Despite the previous comments, some sharp-lined main-sequence stars in the field do pulsate. The cluster surveys may provide some more insight in this regard. The variables in the young Pleiades cluster, but not in the older clusters, show a lower rotational velocity than the non-variables. This difference in the behavior of different clusters also is statistically quite significant. Furthermore, our work presently in progress in the α Per cluster (which is quite similar to the Pleiades) has found another sharp-lined pulsator. If our reasoning in (ii) concerning metallicism and pulsator is correct, we would predict that the slow rotators in the Pleiades should not be Am stars. This would conflict with the generally well-documented rule that slowly rotating A stars are Am stars. A look at the spectral classifications as well as the photometric m_1 index confirms our prediction. Although seven out of fourteen stars in the Pleiades instability strip have $v \sin i < 100$ km s^{-1}, only one (borderline) Am star has been found inside the instability strip. Why the Pleiades slow rotators are δ Scuti variables rather than Am stars still needs to be explained.

3. Metallicism and Pulsation

In the winter of 1970 the variability survey of the stars in the Praesepe cluster was completed and one fact stood out: the classical Am stars did not pulsate. An analysis of the previously available field and cluster variability surveys confirmed the 'new' finding. We had previously found a supposed field Am star, HR114, to be variable, but the spectral classification in the literature was inappropriate. The lack of δ Scuti variables among the Am stars was announced several months later (Breger, 1970). Since then we have tested numerous other Am stars for pulsation and found none. Other investigators also attempted to see if the exclusion between metallicism and pulsation on the main sequence is absolute, and two Am stars have since been reported to be δ Scuti variables: HR5491 (Bessell and Eggen, 1972) and 32 Vir (Bartolini *et al.*, 1972). New observations of HR5491 by several astronomers show that this star is (now) constant in light (Breger *et al.*, 1972; Eggen, 1973). We are presently analyzing a large number of photometric observations of 32 Vir. This star is very unusual in another respect: the spectrum is extremely time-variable, which is not known for either δ Scuti or Am stars. Furthermore, the calcium K-line does not share the 100 km s^{-1} orbital amplitude of the metallic lines (Abt, 1961). 32 Vir certainly deserves more investigation.

Other types of A/F stars with unusual spectral appearance also exist; e.g. the δ Del and F-peculiar stars. Because considerably more data is now available, it is instructive to again look at the pulsation properties of the different types of A/F stars.

We only consider the stars with available spectral classifications by the Cowleys, the Jascheks, Morgan, Bidelman and Abt. We hope that selection of these well-known classifiers provides us with a reasonably uniform means for dividing the stars into distinct groups: Normal and others (metallic). However, A/F stars with an abnormally high photometric metallicity index (m_1 in the *uvby* system) were also put in the second group.

3.1. Normal stars

They show no or very few spectral peculiarities. The photometric metallicity index is normal. Abundance analyses, where available, also indicate normal metals. The pulsation properties of this group are explored in Figure 5. In the instability strip 36 out of 105 stars are δ Scuti variables (34%) and 69 stars were constant in light, at least at the time of observation.

3.2. Unusual stars

This group contains the well-known classical Am stars and our 'cosmic garbage box' of other A/F stars with presently badly understood degrees of metallicity (e.g. δ Del and F-peculiar stars). The classifications of the classical Am stars are generally consistent and their m_1 index is high. Recent work by Smith and others has shown that the individual abundance variations can be understood in terms of rotational velocity and temperature through the Diffusion Theory. A conservative statement about the

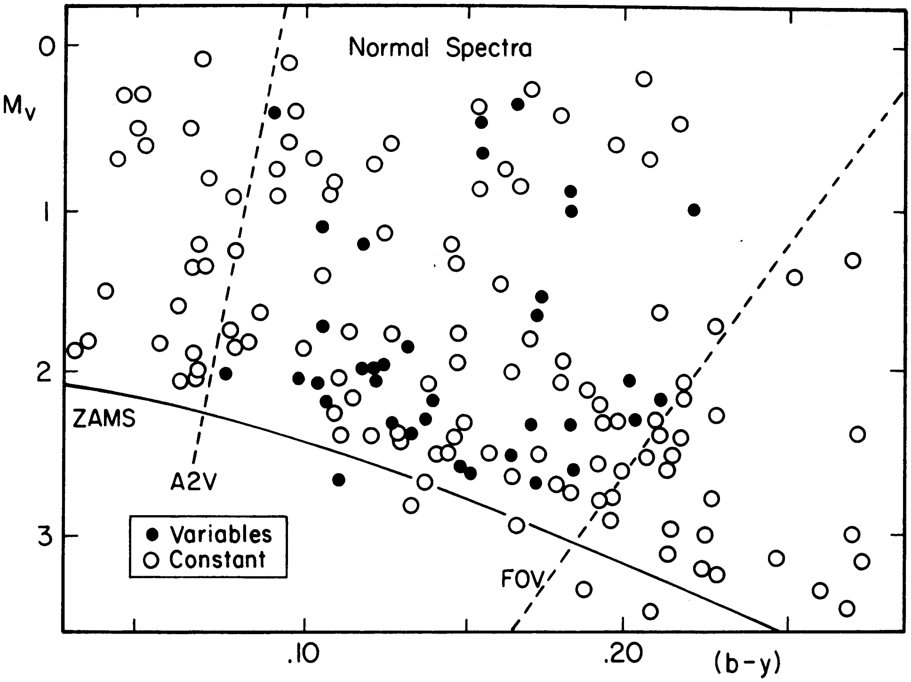

Fig. 5. Incidence of δ Scuti variability among spectroscopically normal stars.

'cosmic garbage box' stars may be that the relationship between the calcium, hydrogen and metallic-line strengths is neither normal nor like those seen in the classical Am stars.

The variability data in Figure 6 shows that among the 27 Am stars inside the instability strip we only find two possible δ Scuti stars (HR 5491, 32 Vir). As mentioned earlier, the δ Scuti variability of these two stars is still rather uncertain. The exclusion of pulsation and metallicism on the sequence, therefore, may or may not be absolute. Irrespective of whether or not HR 5491 and 32 Vir actually pulsate, the paucity of pulsators among the classical Am stars seems well extablished.

A different picture emerges for the other unusual stars in the instability strip (δ Del, F IIIp etc.). Eight our of twelve stars are known pulsators and they include δ Scuti and δ Del. *These variables are all fairly luminous.* A student at the University of Texas, Don Kurtz has been working with us to determine if the spectral anomalies in δ Del and FIIIp stars denote real abundance differences. His preliminary findings from high-dispersion spectra of stars are:

(i) The shapes of the hydrogen and calcium line profiles in many, but not all, δ Del/FIIIp stars are normal. This may be in conflict with one of the spectroscopic classification criteria for δ Del stars.

(ii) Model atmosphere abundance analyses relative to normal stars show that the rare earths in δ Del/FIIIp stars are overabundant by a factor of ~3. This is almost as high as Smith's overabundances for the 'average' Am star in this temperature region.

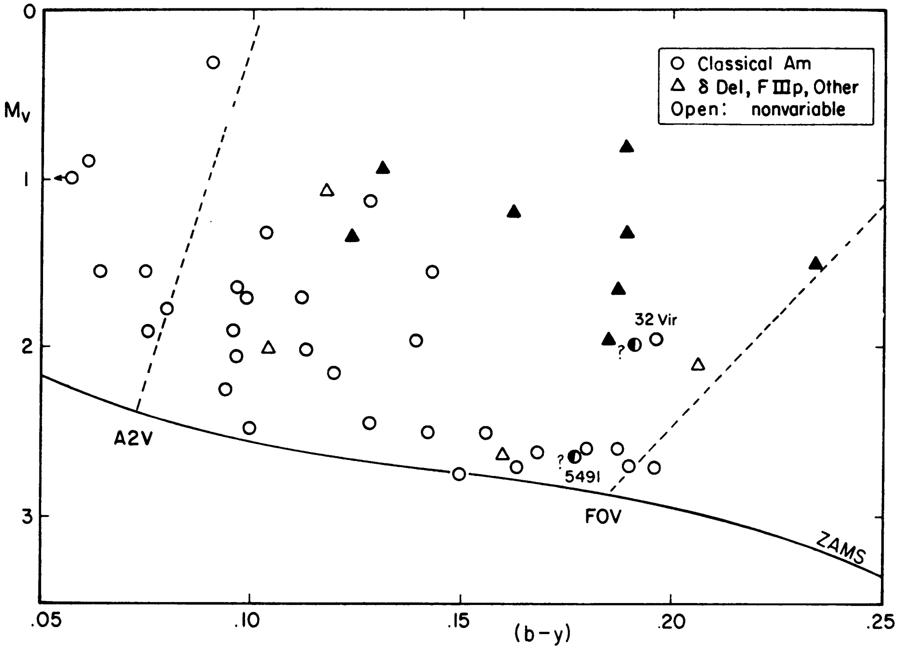

Fig. 6. Incidence of δ Scuti variability among spectroscopically unusual stars. Open circles and triangles refer to constant stars and filled triangles are δ Scuti variables. The half-filled circles are two Am stars with doubtful δ Scuti variability.

Iron, on the other hand, appears almost normal. These abundance analyses confirm that at least some of the δ Del/FIIIp stars do have unusual abundances. So far the spectroscopic work has not determined whether these stars are a special group of stars or just a 'cosmic garbage box' of all A/F stars that do not fit the normal or classical Am criteria.

Why is this important for our understanding of pulsation? Calculations by Baglin (1972) and others have shown that close to the main sequence the pulsation/classical Am exclusion can be explained by the Diffusion Theory due to the gravitational sorting of helium in the outer layers. For slow rotators, element segregation would cause pulsational stability due to low helium in the H II ionization region as well as an unusual metallic spectrum. We have also proposed that pulsation might provide a mixing mechanism which could prevent the formation of Am stars. If the δ Del/FIIIp stars have true abundance anomalies also caused by diffusion, then in a certain temperature and (lower) gravity range, metallicism and pulsation can co-exist.

4. Periods and Pulsation Modes of δ Scuti Stars

The periods of δ Scuti variables are well-correlated with luminosity and color, but a few deviations exist. The correlation is shown in Figure 7 for those stars for which reasonable values of the period, luminosity and color are known.

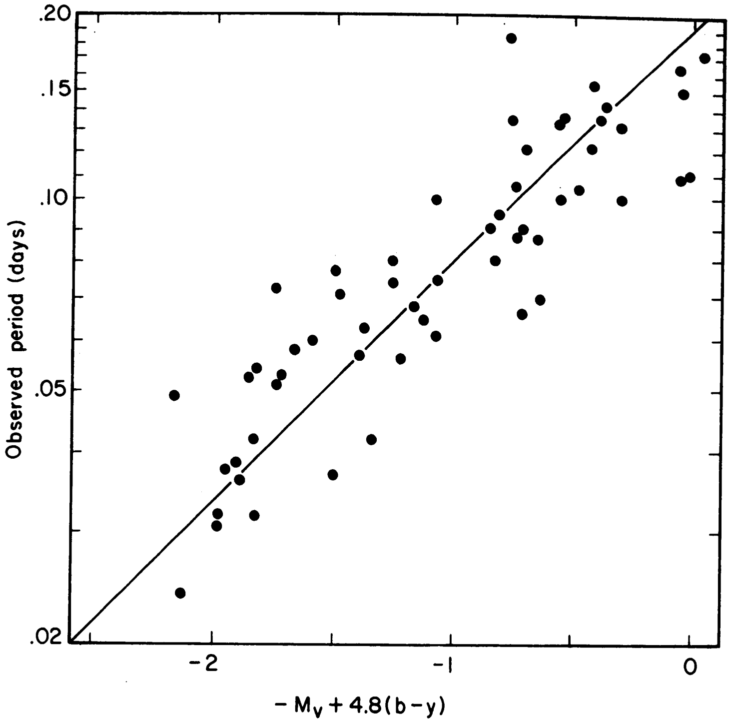

Fig. 7. Dependence of pulsation period on luminosity and color.

The δ Scuti periods are only known to an accuracy of about 8%. The reasons are only partially observational. The δ Scuti variables show real variations in their apparents periods and shapes of light curves. These light curve variations can be explained by:

(i) Nonlinear atmospheric effects (LeContel *et al.*, 1974) rather than a mixture of precise harmonic modes. Presumably, each variable star would have a good average period determined by its luminosity and color.

(ii) Superposition of two or more *radial* modes giving rise to beat amplitudes and periods. A good example of this phenomenon is 21 Mon (Gupta, 1973), for which two periods with a period ratio of $P_0/P_1 = 0.75$ were found. This period ratio is in excellent agreement with theoretical calculations for radial modes.

(iii) Superposition of two or more non-radial modes. A good example may be 1 Mon, a star with spectacular beats. Millis (1973) found two close periods with $P_1/P_2 = 0.98$. Unpublished work by Shobbrook demonstrates the existence of three close periods in 1 Mon. The period ratio of 0.98 is not consistent with radial pulsation. Suppose that we have two degenerate non-radial modes in 1 Mon which are split by stellar rotation. We can then use the observed period ratio to calculate the required rotational velocity for the interference of the $l = 2$, $m = -2$ and $l = 2$, $m = 0$ modes. This leads to a rotational velocity of < 15 km s^{-1}, which is quite compatible with the small measured $v \sin i$ of $\leqslant 25$ km s^{-1}. These arguments are, of course, still quite uncertain. We have to wait for more observations and analyses in order to establish how important non-radial modes really are in δ Scuti stars.

Despite these shortcomings in our knowledge of δ Scuti periods, the average observed periods are reasonably well-known. We have calculated the values of the pulsation constant Q from new information on the periods, luminosities and colors (Breger and Bregman, in preparation). We find the following average values:

$$T_{\text{eff}} > 7800°: \langle Q \rangle = 0.022 \pm 0.001 \text{ days}$$
$$T_{\text{eff}} \leqslant 7800°: \langle Q \rangle = 0.030 \pm 0.001 \text{ days.}$$

If we assume that pulsation is (mainly) radial for the average δ Scuti star, the Q values indicate that the cool variables are pulsating in the fundamental mode, while the hot variables pulsate in the 1st or 2nd harmonic mode (Figure 8). This is quite similar to the division according to temperature in Bailey a, b, c types among the RR Lyrae variables.

The complexity of the light variations of δ Scuti stars is now generally recognized. Several groups are presently working on the multiperiodicity of δ Scuti stars. Some of

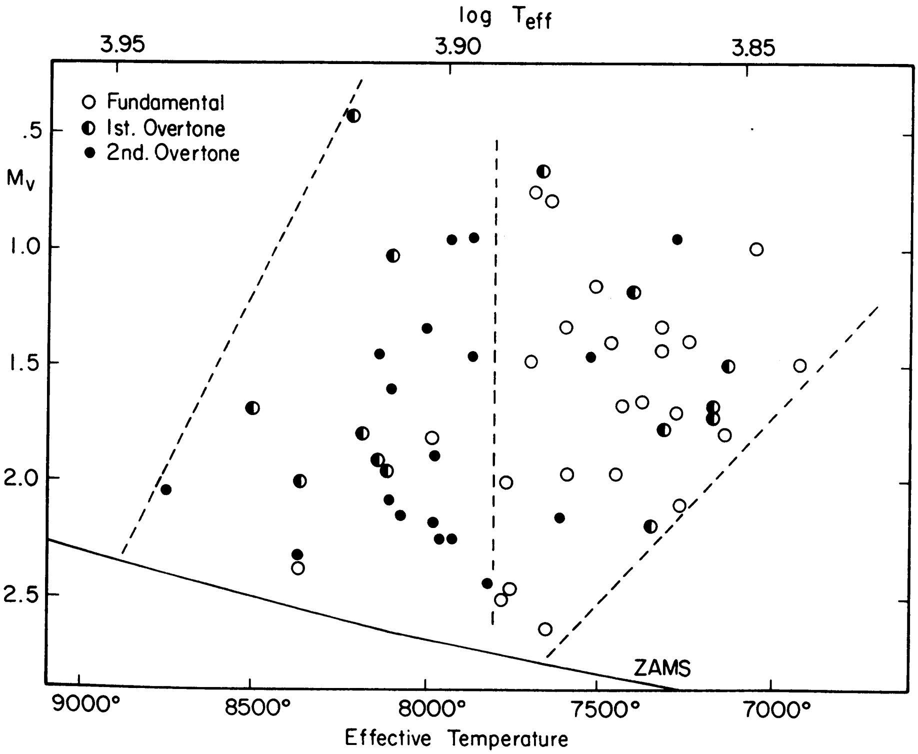

Fig. 8. Derived pulsation modes for known δ Scuti stars as a function of luminosity and temperature under the assumption of radial pulsation. The central dashed line denotes a rough division into fundamental and overtone pulsators.

these are: J. Warman and I at the University of Mexico and McDonald Observatory; Shobbrook in Australia; Millis and Fitch in Arizona; the large French group (e.g. LeContel, Baglin) at the University of Nice and a group in India (e.g. Gupta). The next few years should prove to be very exciting.

References

A full set of references for the work up to 1972 can be found in the review paper by Baglin *et al.* (1973).

Baglin, A.: 1972, *Astron. Astrophys.* **19**, 45.
Baglin, A., Breger, M., Chevalier, C., Hauck, B., LeContel, J. M., Sareyan, J. P., and Valtier, J. C.: 1973, *Astron. Astrophys.* **23**, 221.
Cox, A. N., King, D. S., and Tabor, J. E.: 1973, *Astrophys. J.* **184**, 201.
Eggen, O. J.: 1973, *Quarterly J. Roy. Astron. Soc.* **14**, 436.
Gupta, S. K.: 1973, *Observatory* **93**, 192.
Jakisch, G.: 1972, *Astron. Nachr.* **294**, 1.
LeContel, J. M., Sareyan, J. P., Valtier, J. C., Baglin, A., and Zribi, G.: 1974, *Astron. Astrophys. Suppl.* **15**, 115.
Millis, R. L.: 1973, *Publ. Astron. Soc. Pacific* **85**, 410.

DISCUSSION

Yu. S. Romanov: Do stars exist with differences in spectral classes as derived from hydrogen, calcium and iron lines in the δ Scuti class?

M. Breger: This question is not yet answered. There is no sharp division between metallic-line stars and 'normal' ones. Obviously the same question exists among the δ Scuti stars.