DELTA SCUTI STARS AND DWARF CEPHEIDS: REVIEW AND PULSATION MODES

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ABSTRACT

Recent developments in the field of Delta Scuti stars are discussed. Considerable progress has been made in determining the multiple-period structure of individual variable stars and in identifying the excited radial and nonradial modes through a variety of methods. This allows an analysis of the change of excited modes as a function of the position in the instability strip.

I. INTRODUCTION

Delta Scuti stars are short-period pulsators of spectral type A and F situated on and above the main sequence. In the past, those variables with visual light amplitudes in excess of 0.3 magnitudes were often called Dwarf Cepheids or RRs variables and regarded as a separate type. The artificial dividing line of 0.3 magnitudes is not meaningful in light of the astrophysical properties of both groups, and both are called Delta Scuti variables. A small subgroup of metal-poor variables (with both large and small amplitudes) exists with SX Phe as a good prototype. The small known number of stars in this Population II subgroup was recently increased by HD 94033 (P = $0\overset{d}{.}0595$, Przybylski and Bessell 1979).

A recent review and summary of the properties of Delta Scuti stars is available (Breger 1979). Good discussions on the topics of tidal modulations, resonances and radial/nonradial mode coupling can be found in two other recent papers (Fitch 1980, Dziembowski 1980).

II. INSTABILITY STRIP BORDERS

Does the Delta Scuti star instability strip have well-defined borders?

Figure 1 (adapted from Breger 1979) shows the distribution of Delta Scuti stars in the H-R Diagram, where (b-y) is the temperature

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indicator, and M_V values were calculated from uvbyβ photometry. The two Ap stars with demonstrated short-period variability have been omitted from the diagram, although this variability may be related to Delta Scuti pulsation. Two stars can be found beyond the cool border. The first star, HR 7859 = ρ Pav has a very uncertain luminosity, since the uvbyβ calibrations probably do not apply to this star with unusual abundances. Kurtz (1980a) makes a strong argument that HR 7859 is probably considerably more luminous as shown in Figure 1.

The second star, HR 4746, was announced to be variable by Eggen (1974). This star appears unusual not only because of its extremely low temperature, but also its short period relative to its luminosity. To check that HR 4746 is indeed variable and has a short period, Carr (Sandmann 1980) has reobserved the star for four nights. He finds no evidence for variability. We conclude that the variability of HR 4746 is very much in doubt, and the cool instability strip border is probably absolute.

III. RADIAL AND NONRADIAL PULSATION MODES: METHODS

The Delta Scuti stars are situated between several other types of pulsators in the H-R Diagram. On the luminous end we find the classical cepheids and RR Lyrae stars, which are radial pulsators.

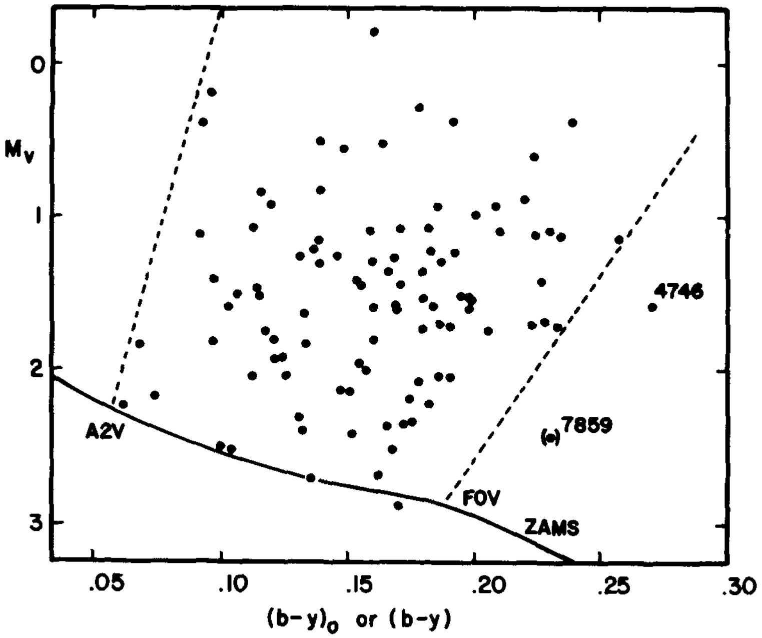

Figure 1 - Observed instability strip borders. Arguments are presented that HR 7859 is much more luminous than given by uvbyβ photometry and that HR 4746 is not variable.

Several magnitudes below the main sequence and the Delta Scuti stars are situated the nonradially pulsating white dwarfs (ZZ Ceti stars). Considerably hotter than Delta Scuti stars are the β Cephei variables (probably with radial and nonradial modes) and the 53 Per variables (nonradial). The strategic location of the Delta Scuti stars suggests that both radial and non-radial modes might be excited in this transition region. Analyses of individual stars show that this naive expectation does indeed describe the real situation.

Most of the different methods of identifying specific radial and nonradial modes require an accurate decomposition of many light or velocity curves into their constituent stable periods. In the literature we can find several reports that some Delta Scuti stars show variable frequencies from night to night, or from season to season. Variable frequencies need to be separated from the situation of an apparently variable light curve due to the beats of perfectly stable multiple modes, or the situation of constant modes with time-variable amplitudes. Truly variable frequencies would have severe consequences in our understanding of these stars, since most of our theories require constant, albeit complex frequencies.

It is virtually impossible to deduce a multiple frequency set from one or two nights of observations of Delta Scuti stars. Consequently, it appears safe to disregard the reports of variable night-to-night frequencies as over-interpretation. Other reports of long-term variations in frequencies by experienced astronomers cannot be simply disregarded, e.g. θ Tuc (Stobie and Shobbrook 1976), 21 Mon (Stobie, Pickup and Shobbrook 1977). In an important recent preprint, Kurtz (1980b) examines the star θ Tuc with new observations and a rediscussion of the previous observations. He shows that the frequency of highest amplitude is present at a constant amplitude over the 7 year time span, e.g. there is little evidence for variable frequencies in θ Tuc. He also argues convincingly against the reported variable frequencies of other stars as well. The star 21 Mon remains an enigma with no known explanation for the apparent frequency change over two years.

Once the multiple frequency structure of a Delta Scuti star has been determined, several methods (some new) can be applied to deduce the presence of radial and nonradial modes:

(i) For radial pulsation specific period ratios such as $P_1/P_0 = 0.76$ and $P_2/P_1 = 0.81$ are expected. A paper by Andreasan, Hejlesen and Petersen later in this volume discusses these ratios in more detail. For higher overtones the method of identifying multiple radial modes by the "magic" ratios may run into difficulties, e.g. due to the "width" of the period ratios, the ratio 0.61 could be P_2/P_0 or P_4/P_1 or even nonradial.

For nonradial pulsation we cannot yet predict specific ratios. Consequently, any observed ratio not agreeing with the radial magic numbers is generally only a sign that one or more nonradial modes are present.

(ii) The *pulsation constant* Q can be computed from the observed $uvby\beta$ indices. For radial pulsation, $Q_0 = 0^d.033$ and $Q_1 = 0^d.025$, while nonradial p modes, for example, have $Q \leq 0^d.025$ (Dziembowski 1980). This method is physically identical to comparing period-luminosity-color relations with observed periods. It works best for stars of normal abundance, since the photometric calibrations used to calculate Q apply mainly to normal stars.

(iii) Accurate measurements of spectroscopic *line profiles* with appropriate modeling can separate radial from nonradial modes (Campos and Smith 1980). Recent data (Smith 1980) clearly pinpoint the existence of several radial as well as nonradial modes in different stars, but the method cannot determine the modal constants (k, ℓ, m).

(iv) The observed *phase lag* between the light, color and radial velocity variations depend on ℓ, the spherical harmonic order of the pulsation mode (Balona and Stobie 1979a; also see the papers by Balona, Kurtz and Stobie later in this volume). In particular, the phase lags between the light and color curves have recently been applied to determine ℓ.

(v) *Amplitude ratios* between light, color and radial velocity variations also depend on the nature of the excited modes. For example, the velocity scale factor across the projected stellar surface, β_ℓ, depends on ℓ. For odd values of ℓ, $\beta_\ell = 0$ (Balona and Stobie 1979b). This method is essentially a modified Wesselink analysis.

IV. RADIAL AND NONRADIAL PULSATION MODES: RESULTS

The methods outlined in the previous section have revealed an interesting variety of behavior in Delta Scuti stars. The large-amplitude variables ($A_V > 0^m.3$) show only one or two excited modes with period ratios and Q values indicating pulsation almost always in the radial fundamental (and occasionally in the 1st radial overtone) mode.

Many of the small-amplitude variables, on the other hand, show a complex mixture of radial and nonradial modes. It would, however, be inappropriate to conclude that all small-amplitude variables are complex: Table 1 shows the results for three small-amplitude variables: HR 6434 and ρ Pup (both simple), and δ Scuti itself (complex).

The different methods of pinpointing the excited radial and nonradial modes are usually in good agreement with each other. In fact, mode assignments based on the "classical" methods of period ratios and Q values are confirmed by the other, more recent methods. Q values show that the excited radial modes have $k = 0, 1, 2$ (fundamental, first, and second overtones) and that the Q values of the nonradial modes are

TABLE 1

PULSATION MODES IN THREE DELTA SCUTI STARS

HR 6434:

Multiperiodicity Analysis: Only 2 periods (Loumos 1980). Excellent fit to a decade of data. Amplitudes are $0^{m}.016$ and $0^{m}.007$.

Period Ratios: *Radial* F + 1H.
Q Values: *Radial* F + 1H.

ρ Pup:

Multiperiodicity Analysis: Single period (Ponsen 1963)
Q Value: *Radial* F
Line Profiles: *Radial* (Campos and Smith 1980)

δ Scuti:

Multiperiodicity Analysis: Complex behavior, many frequencies.
Period Ratios: (e.g. Fitch 1975)

$0^{d}.194$, $A_V = 0^{m}.744$, *radial*

$0^{d}.116$, $A_V = 0^{m}.012$, *radial*, period ratio 0.60

$0^{d}.187$, $A_V = 0^{m}.030$, *nonradial*, period ratio 0.964

Q Values:

$0^{d}.194$ is *radial* fundamental

$0^{d}.187$ is not a p mode.

Line Profiles: (Smith, unpublished)

$0^{d}.194$ seen in radial velocity, little effect on profiles. *Radial.*

Profile variations show a nonradial mode near, but not at $0^{d}.194$. Suggests $0^{d}.187$ photometric period is *nonradial.*

More *nonradial* modes also present?

Phasing and Amplitude Ratios: (Balona, Dean and Stobie 1980)

$0^{d}.194$ is *radial.*

$0^{d}.187$ is *nonradial*, quadrupole nonradial ($\ell = 2$)

usually shorter than $0\overset{d}{.}025$, in full agreement with expected values for p modes.

A small disagreement remains for the star δ Scuti. The reported period ratio of 0.60 has been interpreted as fundamental radial pulsation for the main excited mode (Fitch 1975), which is also confirmed by the Q value. The period length of the main nonradial mode, on the other hand, would then predict Q(NR) = $0\overset{d}{.}032$, which appears too high for the reported quadrupole p mode.

Enough data on Delta Scuti stars is now available to allow a study of the systematics across the instability strip in the H-R Diagram. Historically, multiperiodic solutions have been rather poor at predicting future ephemerides in these stars. This advises caution in accepting recent results as well. To maximize chances for accuracy, only the multiperiodic solutions (published and unpublished) with a reasonably good fit to existing data were chosen for our analysis. This criterion is, of course, also imperfect. We retain 25 small-amplitude stars with "known" multiple periods, absolute magnitudes from uvbyβ photometry, and pulsation mode identification determined from some of the five methods listed in the previous section.

What is the main excited mode in Delta Scuti stars in different parts of the H-R Diagram? Light amplitude is one such indicator, although for some higher-order nonradial modes cancellation effects occur across the projected stellar surface. Figure 2 shows which identified mode has the highest amplitude, A_V, for small-amplitude Population I Delta Scuti stars ($A_V < 0\overset{m}{.}3$). The symbol "N" may have different meanings: situations where the dominant mode is nonradial (e.g. HR 7331, Smith 1980) or pairs of dominant modes where at least one component has to be nonradial (e.g. HR 8880, Loumos 1980). We note the following:

(i) In many stars several radial modes are excited at the same time. The radial fundamental (F) appears to be dominant mainly in the cool part of the instability strip. The observational data is insufficient to examine whether or not a unique blue edge for F exists cooler than the hot instability strip border. We can conclude that in cool variables F tends to have larger amplitudes than the other modes.

(ii) Even where pulsation is mainly in a higher radial overtone, a lower overtone and F may still be excited as well. An example is the star 38 Cnc, where the second radial overtone, 2H, has a much larger amplitude than 1H and F.

(iii) Variables with very large amplitudes in excess of $0\overset{m}{.}3$ belonging to Population I (ex-Dwarf Cepheids, not plotted in Figure 2) have a less complex multiple-period structure. They are pulsating in F, with 1H sometime excited as well. (The star VZ Cnc is an exception with 1H + 2H.) If these stars were plotted in Figure 2, they would fall in the upper right quadrant with symbols "O".

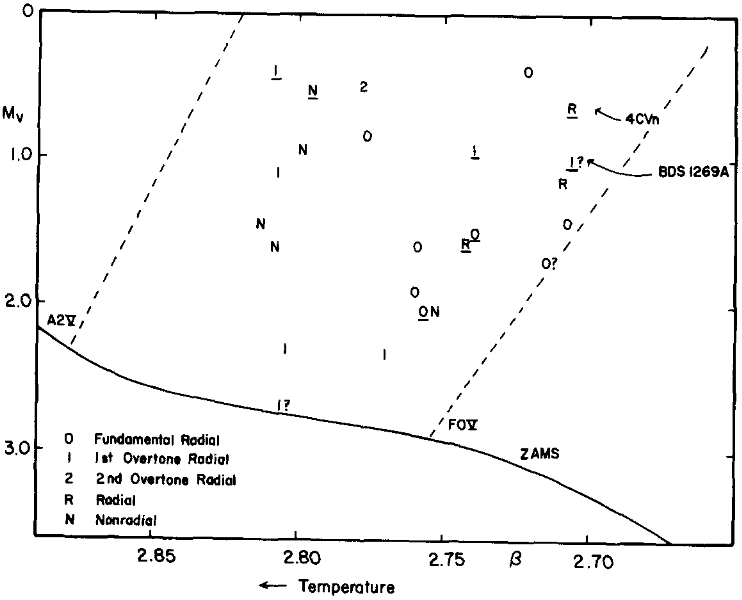

Figure 2 - Identification of the pulsation mode with the highest amplitude in small-amplitude variables ($A_V < 0\overset{m}{.}30$). Underlined symbols imply that an additional mode has been identified and found to be due to nonradial pulsation. Large-amplitude Pop. I variables are not plotted. They would fall in the cool giant and subgiant region (upper right quadrant) and are mostly radial fundamental pulsations (Symbol "O").

(iv) Nonradial pulsation occurs across the whole Delta Scuti instability strip but not in every star. Nonradial pulsation often coexists with radial modes in the same star. It is an interesting speculation that the radial and nonradial modes are not independent of each other, but coupled through resonances or rotation. The physical reasons for the stars' selections of particular pulsation modes deserve much more study.

The observed systematics across the instability strip allow speculation about the largely unanalyzed region near the blue border. For hot stars the dominant radial modes are higher overtones ($k \geq 1$), which have relatively closely-spaced periods. At the same time, these overtone radial periods are also close in length to expected nonradial periods. In the presence of multiple modes, the observer will see a very complex light curve with <u>small</u> average amplitudes. Multiple-frequency analyses will be difficult. In fact, one wonders whether the observed blue instability strip border might not be the place where the sum of all the excited high-order ($k \geq 3$) radial and nonradial modes with small amplitudes leads to vast cancellation effects with apparent light constancy at some times and sporadic light variability with no apparent periodicity at other times. Such a behavior is characteristic of the mythical Maia variables, which have occasionally been reported to the blue of the Delta Scuti variables and whose reality has never been confiremd.

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DISCUSSION

SIMON: Is the amplitude of HR 6434 $0^m.2$ or $0^m.02$?

BREGER: The amplitude is $0^m.02$. This is a problem. If Dziembowski is right and the amplitudes are limited by mode coupling between many radial and nonradial modes then HR 6434 does not fit because it only has two modes and has small amplitude.

SIMON: For a star like δ Scuti the three periods that we see repeat, but what about the power? Is that constant also?

FITCH: There is practically no change from 1953 to 1970.

SMITH: With regard to the blue border of the instability strip, I would like to point out that there are still a lot of sharp lined stars which are chemically peculiar in this region, particularly the mercury-manganese stars. The 53 Per stars cut out right where this chemical composition anomaly begins and there is some evidence that slow rotation may be favored both in these stars and in the δ Scuti stars. So, in view of that I would like to suggest that there may be no continuity between the two groups.

STOBIE: What is your opinion regarding the stability of the frequencies and amplitudes of these stars? I gather from what you said that it is necessary to deal with small data sets. Do you feel that the variations that have been suggested by some people are real or the result of inadequate data sets?

BREGER: I am convinced by Kurtz's recent paper in which he makes the point that the frequencies are stable in these stars. There is only one star left which is somewhat doubtful and that is 21 Mon. Maybe you could comment on that. Everything seems to indicate that the frequencies are stable. The question is, are the amplitudes stable? I tend to favor the hypothesis that they are not necessarily stable. We have heard that they are stable in δ Scuti, in ρ Puppis, and many other stars, but there may be some others, 38 Cancri is one, where they don't seem to be stable and I would not be disturbed by this because we have already heard that 16 Lacertae changed all of its amplitudes by a factor of two over ten years. The frequencies stayed the same and the amplitudes went down. That is well documented unlike amplitude changes in δ Scuti stars. Therefore, I would not be surprised if amplitudes actually changed in some δ Scuti stars, especially nonradial ones. Whether or not radial amplitudes change remains to be seen.

ROBINSON: As you know, there are in principle some other ways to decide whether a mode is real or not. For example polarization. Did you have some reason for leaving that out of your discussion?

BREGER: Someone like Odell should make a calculation of how big polarization would be if it is as small as 0.01%. I personally feel that it is almost unobservable, but if it is larger, it would be a beautiful new method. We need more methods. It is nice that we now have five instead of just two. Once we get seven or eight we will really be in business.

FERNIE: How accurately do those borders of the instability strip extrapolate onto the Cepheid borders?

BREGER: It turns out to be fairly exact. I think that is an accident because you have stars of different masses, different compositions, and they are in a different evolutionary state.

SIMON: There are also RR Lyrae stars on the top of your strip which you haven't talked about. Some of them have metals that seem to be normal population I.

BREGER: Yes, and I wish that we knew their luminosities and masses. Could it be that some of these are actually very luminous δ Scuti stars? In other words, population I stars with high mass. We don't expect too many in the galaxy because the evolution from left to right for luminous stars is very fast, but we expect some and maybe one, or perhaps many of these RR Lyrae stars with normal metals are just very luminous stars going from left to right.

PERCY: I am intrigued by the so-called Maia stars and I wonder if when you get to that part of the H-R diagram the light amplitudes are gone completely, but you get a certain mixture of modes that produces profile variations that masquerade as velocity variations if you are not careful?

BREGER: That is an excellent suggestion. It may be that to look for light variations is not the way to go. Maybe you should look for profile variations.

J. COX: What is your opinion about the mass of SX Phe?

BREGER: I can reiterate the conclusions that we came to in our study, and I still believe them. The vast majority of these large amplitude stars, so called dwarf Cepheids, are in fact population I δ Scuti stars with an amplitude which is slightly larger. There is a subset of the large amplitude variables, and indeed of the small amplitude variables as well, which are very metal poor and, therefore, are not normal population I stars. In the case of SX Phe I think that one of two hypotheses should fit. Either it is a population II star which is on its own main sequence, which is lower than the population I main sequence implying a mass of about 1.1 $M_{\odot}$ according to A. Cox and others, or the star has experienced enormous mass loss and has a mass of about 0.4 or 0.5 $M_{\odot}$. In either case they don't fit the standard evolutionary scheme because hot population II stars should not exist and such large mass loss has not yet been demonstrated. It is therefore very important to find out whether the mass of a star like SX Phe is 0.4, 0.5, 0.6 or 1.1 $M_{\odot}$. I have not been able to do this and, in my view, nobody else has been able to determine the mass or radius that precisely. I think it can be done with more work and it should be attempted.

A. COX: How?

BREGER: One way would be to use a modern Wesselink method.

A. COX: What is the status of that? It seems to me that Jorgensen or somebody did something on that and came up with a difficulty.

PETERSEN: Yes, he found that it was very difficult to analyze data for SX Phe.

FITCH: I think that the problems with δ Scuti are still much more severe than you indicated.

BREGER: I hope that there will be more work done on the star. If you cannot solve δ Scuti, which has a big amplitude with lots of observations, then maybe we can't solve the other ones.