Period Changes in δ Scuti Stars

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Abstract The δ Scuti stars are pulsating variables useful for studies of stellar structure and evolution. Though new and improved models of stars and stellar physics have increased our understanding of these variables in recent years, some aspects of their behavior such as *period changes* are still poorly understood. Period changes may arise from a variety of evolutionary and non-evolutionary causes including undiscovered binarity, nonlinear mode-coupling, and secular changes in chemical structure. In this review, I will briefly summarize current observations and theories on period changes in δ Scuti stars, and suggest ways that the AAVSO community can contribute to this important field.

1. The δ Scuti stars

The δ Scuti stars are a class of *pulsating variable star* that lies on the Cepheid instability strip, and are driven by the same variability mechanism (the κ- or "opacity" effect) that drives both the Cepheids and the RR Lyrae stars. They are the "smaller cousins" of the Cepheids, having lower masses (1.0–3.0 $M_{\odot}$), lower luminosities (10–50 $L_{\odot}$), shorter periods (0.03–0.3 day), and smaller amplitudes (generally less than a few tenths of a magnitude peak-to-trough). The δ Scuti stars exhibit a very wide range of behavior; these stars lie near where the instability strip crosses both the zero-age main sequence and the main sequence turn-off (spectral classes A–F), so the class contains a mixture of pre-main sequence, main sequence, and post-main sequence stars, each having their own characteristics. δ Scuti stars are present among both Population I and II stars; the low-metallicity Population II stars are known as *SX Phoenicis stars*, while the higher metallicity Population I stars are simply known as δ *Scuti stars*.

The most commonly-used subdivision of the class is the distinction between low- and high-amplitude pulsators. The high-amplitude stars (0.1 magnitude or greater) are post-main sequence stars believed to be pulsating in one or more *radial* (i.e. spherically symmetric) modes, although they may occasionally have low-amplitude, non-radial modes in addition to the main pulsation mode (e.g. Poretti 2003). These are the "dwarf Cepheids" which are still commonly discussed in literature. The low-amplitude stars have a wide range of behavior, with single- or multiple-mode pulsations possible in both radial and *non-radial* modes. The low-amplitude stars are found throughout the lower instability strip and include stars of all ages, from newborns to highly evolved stars approaching the red giant branch. They can also pose a difficult observational challenge for photometrists; δ Scuti stars have been found with amplitudes *less than one millimagnitude*.

The study of δ Scuti stars in general has had several useful applications in astronomy and astrophysics. The low-amplitude, multiply-periodic stars have been used for *asteroseismology*—using pulsations to test models of stellar interiors—and are frequent targets for multi-site photometric campaigns to measure and refine their rich pulsation spectra. The high-amplitude stars, like their larger Cepheid cousins, are useful as distance indicators because of their period-luminosity relation; despite having lower absolute magnitudes than both the RR Lyrae and the Cepheids, they may still be used to measure distances to open and globular clusters in the Milky Way, as well as to the Galactic bulge.

2. Period changes in δ Scuti stars

Like the Cepheids and the RR Lyrae, the δ Scuti stars also show long-term period changes, the causes of which are not generally known. In their reviews of the field, Handler (2000) and Breger and Pamyatnykh (1998) noted that the majority of period changes observed in δ Scuti stars greatly exceed the rates expected from theoretical models of stellar evolution, for both the metal-rich stars and the metal-poor SX Phoenicis stars. Breger and Pamyatnykh (1998) found that the inclusion of convective core overshooting could improve the agreement between theory and observations for some Population I stars, but that it could not fix everything. They also noted that nearly equal numbers of positive and negative period changes are seen, also contrary to stellar evolution models. All of this strongly suggests that *evolution alone cannot explain the period changes observed in* δ *Scuti stars*. Handler (2000) suggests that interactions between pulsation modes may be a factor in period changes in multiply-periodic stars, which raises the possibility that we have reached the limits of what simple linear pulsation models can achieve. However, Szeidl (2000) points out that two very simple reasons *may* lie behind many of the large changes seen, namely, (1) poorly defined or missing times of maxima, and (2) undiscovered binarity. Thus, the observed "strange" period changes may in some cases be explainable in terms of known phenomena, rather than requiring as-yet unexplained stellar physics.

2.1. Evolution or not?

Investigations of period changes in the context of theoretical evolution models include Percy *et al.* (1980), Rodriguez *et al.* (1995), and Breger and Pamyatnykh (1998). All three made the statement that the period changes observed in many δ Scuti stars were too large, and about half had the wrong sign (negative, decreasing period) to be explained by standard evolutionary models.

Figure 1 shows the first two radial mode periods versus time for a pair of stellar evolution models lying within the δ Scuti instability strip (Templeton 2000). As the figure shows, the periods of radial modes *increase* for most of the time these stars spend within the δ Scuti instability region. Although *non-radial* modes are not shown on this diagram, it is believed that the pulsations of the high-amplitude stars commonly investigated for period changes are radial-mode pulsators, and thus *should* follow this behavior. The one stage of evolution when the periods may *decrease* is the brief period of contraction during which the hydrogen-burning core runs out of fuel. This phase is relatively short—a few tens of millions of years, compared to the billion years they may take to evolve from the main sequence to the red giant branch—and we are more likely to see period increases than decreases if evolution is the sole cause.

The values of $d \ln P/dt$ (where P is the period and t is time) expected in the δ Scuti stars vary as the curved tracks in Figure 1 show; Breger and Pamyatnykh (1998) note that rates of period increase are on the order of a few times 10^{-9} y^{-1} on the main sequence, but can increase to 10^{-7} for the most massive post-main sequence pulsators, and even higher for stars still undergoing pre-main sequence contraction. The rates of period change actually *observed* in the δ Scuti stars are typically in the range of 10^{-8} y^{-1} or higher. Clearly these rates are too high for main sequence δ Scuti stars, and sometimes exceed the rates expected for post-main sequence stars as well. Enormous period changes are observed in stars with non-radial modes (e.g. XX Pyxidis, see Handler *et al.* 1998), so clearly something else must be going on.

Period decreases from evolutionary processes will still occur. One possible example is DY Herculis. Although Pócs and Szeidl (2000) claimed the period variations were marginally consistent with binarity, Derekas *et al.* (2003) showed that the period change of DY Her is best fit by a linear period decrease of about -2.8×10^{-8} y^{-1}. A linear period change is expected on observable timescales, and the magnitude of the rate of period change is reasonable for the post-main sequence stage of evolution, where DY Her is expected to be. The problem in this case is with the sign, which indicates a period *decrease*. If, as expected, DY Her (and all other high-amplitude δ Scuti stars) is a radial pulsator, a period decrease is *only* possible during a very short period of time, and it is unlikely—but not impossible—that we would observe a star during that brief stage of its life. The fact that we observe such a wide variety of period changes in δ Scuti stars suggests that evolutionary origins for any period changes would be difficult to prove unambiguously.

2.2. "Simple" answers: undiscovered binarity, observational effects, and subjective interpretation

As Szeidl (2000, 2005) pointed out, period changes in δ Scuti stars *may* have causes that do not require cutting-edge physics such as chemical diffusion, rotation effects, or non-linear mode-coupling. Two important possible causes are light-time effects from previously undetected binarity, and observational errors in determining times of maximum. Both of these raise important questions which are worth exploring.

Probably the best example of binarity causing a period change in a δ Scuti star is SZ Lyn (Moffett *et al.* 1988; Paparo *et al.* 1988). Its (*O–C*) diagram has a clearly sinusoidal signature with semi-amplitude of ~0.007d, indicating light travel time effects are cyclically changing the observed period. The most recent work of Derekas *et al.* (2003) shows that the orbital period is 1190 ± 5 days. Interestingly, Derekas *et al.* (2003) also noted the presence of a long-term trend in the (*O–C*) diagram of SZ Lyn in addition to the sinusoidal component, though they are uncertain whether the trend is parabolic (indicating a period change) or linear (indicating a different but constant period). If it is parabolic, the rate of period change ($+5 \times 10^{-8}$ d^{-1}) is reasonable for an evolutionary period change.

Binarity has been suggested for other stars such as DY Her (Szeidl 2000), BE Lyn (Kiss and Szatmáry 1995), and BS Aqr (Szeidl 2000), though this interpretation has been disputed for (at least) the first two (Derekas *et al.* 2003 and Szeidl 2000, respectively). In all cases *except SZ Lyn*, the period of the purported binarity is close to that of the duration of the (*O–C*) measurements, making it difficult to prove that the signal is truly sinusoidal. A sinusoidal interpretation is only reliable when multiple cycles are recorded, as in SZ Lyn. While the binary hypothesis is certainly *possible* in most of these cases, conclusive proof will not be available for years or even decades to come. Continued monitoring of times of maximum will be crucial, and such observations are encouraged. In the meantime, however, other possible interpretations of their behavior must also be explored.

Observational effects and subjectivity can also affect (*O–C*) analyses. The fact that analyses of individual stars by different observers—sometimes separated by only a few years—can lead to significantly different claims on the star's nature suggests that (O–C) analysis needs to be done with great care. For example, the debate about the period change observed in DY Her has focused on whether it is a binary or simply undergoing a linear period change. Pócs and Szeidl (2000) claimed a binary origin of the observed (*O–C*) variation was *possible*, while the Derekas *et al.* (2003) analysis, which includes a slightly longer span of observations, seems to favor a parabolic trend in (*O–C*). The available span of data may be too short in this case to distinguish between the two, particularly if the orbital period of a (hypothetical) binary system is as long or longer than the available historical record.

One purely observational effect is the use of multiple photometric systems and detectors. Most time-of-maximum databases are obtained with a mixture of visual, photographic, photoelectric, and CCD observations. Because pulsations involve a change in temperature, the peak wavelength of the stellar spectrum changes over the course of the pulsation cycle. Thus the light curves of pulsating stars can look very different in different bandpasses, to the point where a time of maximum measured in red light may be slightly different than one measured in blue. Visual and photographic observations may have the additional complication that the recorded time may be of slightly less precision than one of a photoelectric or CCD observation. And all observations can suffer from errors in reporting time, and poor photometric conditions at the time of observation.

Another observational effect is the interference of two or more pulsation modes present at the same time, which can introduce a systematic "error" in the time of maximum of the dominant period, mimicking a period change. One example of this is the double-mode star AE UMa. Hintz *et al.* (1997) suggested that the period of AE UMa was changing, and their available set of observations sparsely covering JD 2428632–2450516 indicates a very large period change of about 5 $\times 10^{-7}$ y^{-1}. Later, Pócs and Szeidl (2001) re-analyzed the same data and found essentially *no* period change of the dominant mode; their results were duplicated by Zhou (2001). At least two reasons for the discrepancies were found. First, the secondary pulsation mode was causing a shift in the times of maximum of the dominant period. By pre-whitening the photometry with the secondary period, the light curve of the dominant period could then be analyzed and a more consistent set of times of maximum obtained. Second, Pócs and Szeidl (2001) showed that cycle counts of the earliest data could be discordant, and that an adjustment of the cycle numbers of the earliest data by +1 eliminated the strong parabolic trend in its entirety. This highlights a more general problem in (*O–C*) analysis using data with gaps, particularly when these gaps can extend for tens of thousands of cycles. One ambiguous cycle can have an enormous effect on the (*O–C*) diagram, which makes the continuing work of the observational community critically important—every observation really does count!

Several more δ Scuti stars investigated for period changes are known to have secondary periods, including SX Phe (Thompson and Coates 1991), VZ Cnc (Arellano Ferro *et al.* 1994; Fu and Jiang 1999), and V1162 Ori (Arentoft *et al.* 2001). In the case of secondary periods very close to the dominant one, the variations in (*O–C*) can strongly mimic those of binarity. That is likely the case with V1162 Ori (Arentoft *et al.* 2001), where several low-amplitude modes are present in the star and the dominant period appears to vary on a 258-day timescale. Because there are amplitude variations with the same period, it is likely the (*O–C*) variations arise from photometric interference of multiple modes, rather than binarity, although Arentoft *et al.* still list binarity as a possible cause. As Arentoft suggests, the only way to reliably prove the binary hypothesis is with spectroscopy.

2.3. Not-so simple causes for period changes

The number of possible explanations for period changes is limited as much by fundamental physics as by the imagination of theorists involved in studying them. The astrophysics of stars have been extensively studied for more than a century now, but our understanding of how stars behave in real life is still limited. Astrophysical problems such as large- and small-scale convection, element diffusion, stellar rotation, opacity and equation of state physics, and magnetic fields and activity cycles are all very rich and active topics of debate. All of these things can affect the way stars behave on both short and long timescales, and all can potentially have an effect on how pulsation periods can change. Further complicating the physical picture is that the δ Scuti stars often have multiple pulsation modes, and in the case of high-amplitude pulsation or rotation, the interaction between these pulsation modes is poorly understood. Sometimes the secondary modes may simply cause observational interference, as in the cases of AE UMa and V1162 Ori discussed above, but it is possible the modes may physically interact with one another, or even change the structure of the star over time. Ultimately, attributing period changes to any of these phenomena would be speculation at best; there is as yet little physical basis to prove one cause over another.

The RR Lyrae stars have long been known to exhibit complex period variations, and the physical picture for those stars is similar to that of the δ Scuti stars. A good summary of period changes in RR Lyrae stars may be found in Smith (1997). Although the δ Scuti and SX Phoenicis stars are in a much younger evolutionary phase than the RR Lyrae stars, the physical mechanisms for their pulsations are nearly identical, and it is reasonable to assume they could show similar behaviors *if* period changes are a pulsational rather than evolutionary effect, and if the underlying physics are common to both stars. For example, the theory of Sweigart and Renzini (1979) that semiconvection—a convective instability driven by gradients in composition—could drive period changes in some RR Lyrae stars may also hold in highly evolved δ Scuti stars with well-established hydrogen-burning shells (see Hansen *et al.* 2004 for an overview).

The star BE Lyn shows a very complex period history, and the (*O–C*) diagram is not well fit by any simple function, periodic or otherwise. Derekas *et al.* (2003) analyzed this object in great detail, and found no satisfactory answer as to the form of the period change. They made no guess as to the cause other than ruling out binarity. Some RR Lyrae stars are known to have abrupt or otherwise complex period changes, and BE Lyn may be exhibiting the δ Scuti analog of this process. More observations are clearly warranted of this and other stars with similarly strange behavior.

One final problem which is not often addressed is the possibility that the δ Scuti stars are not as strictly regular as we like to believe. Many classes of pulsating variables are known to have cycle-to-cycle variations, with the Mira variables being the most obvious example. The effect of cycle-to-cycle variations on period estimations has been studied in detail since at least the 1920s (see Eddington and Plakidis 1929; Sterne and Campbell 1937). Jacchia (1975) wrote a useful overview of how random variations can mimic true period changes. Such an idea is usually limited to discussions of stars for which cycle-to-cycle variations are obvious, but Koen (2000) pointed out that it is worth considering for the δ Scuti stars as well. He showed that (*O–C*) data can be interpreted quite differently when the period changes are modeled assuming an intrinsic noise component. One surprising example of this is the star XX Cyg, which has long been assumed to have undergone a single period jump around 1942, with constant periods before and after. A reanalysis by Koen indicated a continuous period change was more likely. Subsequent independent work by Zhou *et al.* (2002) and Blake *et al.* (2003) confirmed Koen's analysis, and Percy *et al.* find that definite random fluctuations are also present (Percy 2005).

The result is that XX Cyg is much less “unique” than it was previously, although its period change is still worth study.

3. δ Scuti stars and the AAVSO

The δ Scuti stars in general have never been a major focus of the AAVSO, primarily because of their low amplitudes. However, there are four δ Scuti stars that have been regularly observed by members of the AAVSO RR Lyrae committee for several years: DY Her, VX Hya, SZ Lyn, and XX Cyg. As an example, Figure 2 shows the (*O–C*) diagram for XX Cyg based upon the times of maximum in the AAVSO RR Lyrae program archives. The data for all of these can be easily integrated into existing databases of times of maximum, and will help those investigating period changes in these objects. Outside of the RR Lyrae program, there are a total of 83 “DSCT” variables and seven “SXPHE” in our validation file, though we have data for only a few of these, and charts for fewer still. A list of important δ Scuti and related stars in the AAVSO validation file is given in Table 1. Most known δ Scuti stars have too small an amplitude to be visually observable, and some are even out of reach of most CCD observers as well—many δ Scuti stars require *millimagnitude* photometric precision. Despite these challenges, the AAVSO observer community can contribute to the study of many δ Scuti stars, and we are working on developing charts and an observing program to improve our coverage of these important objects.

The observing community can contribute to the science of δ Scuti stars in two ways. First, continued measurement of times of maximum as is currently done for RR Lyrae stars (and times of minimum for eclipsing binary stars) provides the easiest means of studying period changes. Very long spans of data exist for several stars, and new times of maximum for any of these will help in future studies. Experienced members of the RR Lyrae group may already be observing a few of these, and the AAVSO will work towards supplying visual and CCD charts for additional stars. For now, if you are interested in observing these stars we recommend concentrating on those for which we already have data (see Table 1), since new times of maximum can be easily matched with previous observations and increase the usefulness of what we have.

Second, CCD photometry of these variables can be invaluable in measuring pulsation spectra, particularly when multiple pulsation modes are present. As Figure 3 shows, a single night’s work can yield fascinating light curves for some of these stars, particularly those that have multiple pulsation periods. Each δ Scuti star is unique, and their short periods make it possible to see multiple pulsation cycles in a single evening. Whether you are a visual or CCD observer, and whether you can observe for a single night or week after week, you can help find an answer to the as-yet unsolved problem of period changes in δ Scuti stars.

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Table 1. Selected δ Scuti stars in the AAVSO validation file.

Name	*Desig.*	$m_{V,max}$	*ampl.*	*period(d)*	*chart*	*recommended obs.*
SZ Lyn	0802+44	9.08	0.64	0.1205	yes	visual/CCD
VX Hya	0940–11	10.21	0.75	0.2234	yes	visual/CCD
DY Her	1626+12	10.15	0.51	0.1486	yes	visual/CCD
XX Cyg	2001+58	11.28	0.85	0.1349	atlas	visual/CCD
DY Peg	2303+16	9.95	0.67	0.0729	atlas	visual/CCD
SX Phe	2341–42	6.76	0.77	0.0550	atlas	visual/PEP/CCD

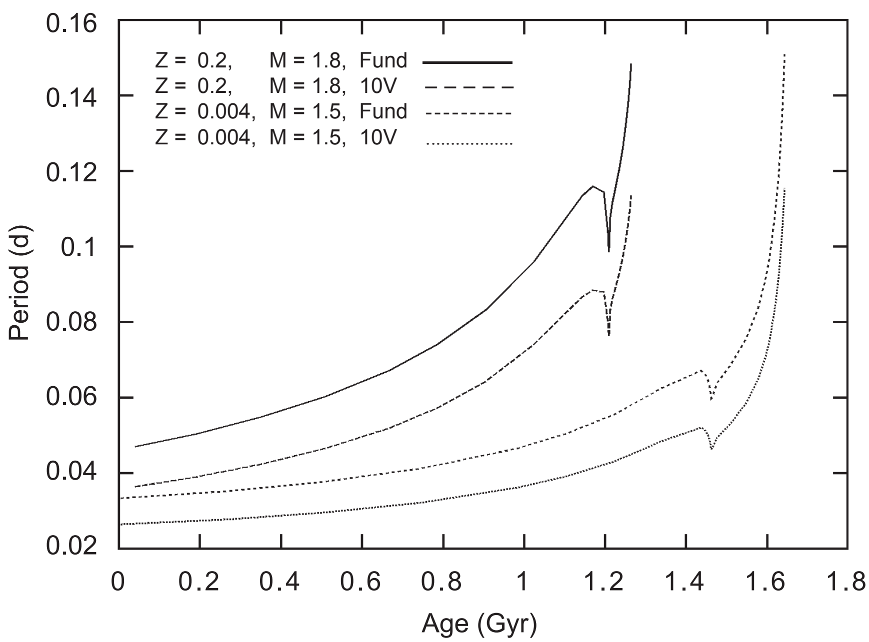

Figure 1. The evolution of fundamental and first-overtone mode periods for two stellar models: a model with an initial metal mass fraction $Z = 0.02$ and mass of 1.8 $M_{\odot}$, and another with $Z = 0.004$ and a mass of 1.5 $M_{\odot}$. The periods of all radial modes are a function primarily of the stellar radius, and the radius increases for most of the main sequence and early post-main sequence lifetimes. Thus we expect that evolutionary period changes should be positive for most δ Scuti stars.

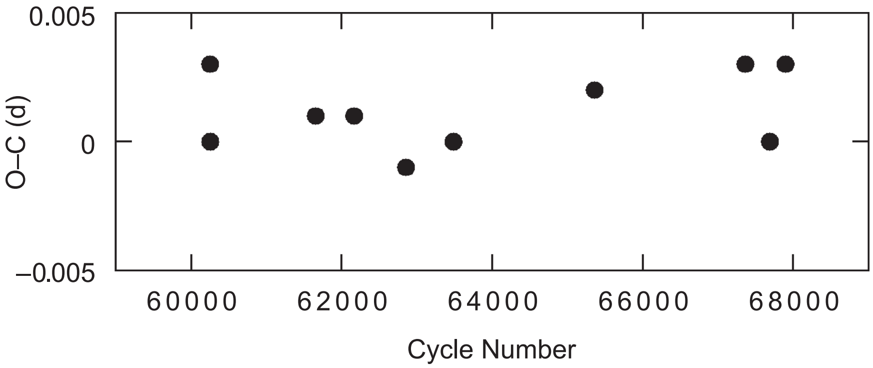

Figure 2. The (*O–C*) diagram of the previous three years for the high-amplitude SX Phoenicis star XX Cyg, based upon times of minimum from the AAVSO RR Lyrae program. The light elements used are Max = JD 2444455.3945 + 0.134865113 E. Courtesy of Gerard Samolyk.

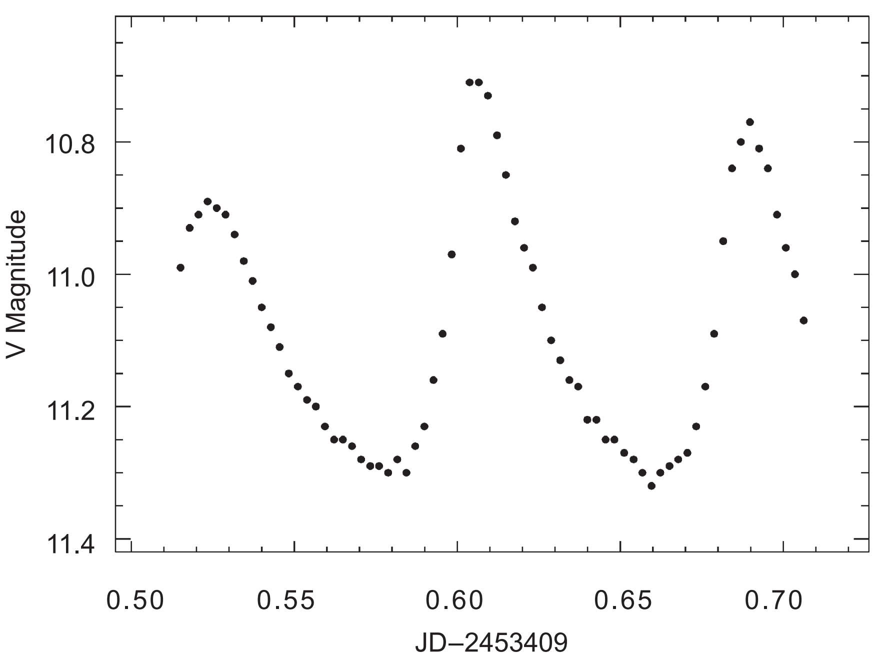

Figure 3. A single-night light curve of AE UMa by Geir Klingenberg (KGE). The primary pulsation period of 0.086 day (about 2 hours) is modulated by a second pulsation mode. The relatively short period and strong modulation make this an interesting target for CCD observers, and we hope to release a chart for this object soon.