Rate of Period Change as a Diagnostic of Cepheid Properties

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ABSTRACT. The rate of period change $\dot{P}$ for a Cepheid is shown to be a parameter that is capable of indicating the instability-strip crossing mode for individual objects and, in conjunction with light amplitude, the likely location of the object within the instability strip. The observed rates of period change in over 200 Milky Way Cepheids are demonstrated to be in general agreement with predictions from stellar evolutionary models, although the sample also displays features that are inconsistent with some published models and indicative of the importance of additional factors not fully incorporated in models to date.

1. INTRODUCTION

Cepheids represent a brief phase in the post–main-sequence evolution of stars that originally had masses in excess of about $3.5 M_\odot$ (Turner 1996). As evolved objects they populate the Cepheid instability strip in the H-R diagram according to the manner in which they generate energy, depending on strip crossing. Intermediate-mass stars can become unstable to radial pulsation during shell hydrogen burning (first crossing), twice during core helium burning (second and third crossings), and according to some evolutionary models (Iben 1965; Becker et al. 1977; Becker 1985; Xu & Li 2004), twice during shell helium burning (fourth and fifth crossings). A common feature of many recent evolutionary models of intermediate-mass stars, which incorporate the new opacity tables (e.g., Meynet & Maeder 2000, 2002; Bono et al. 2000; Salasnich et al. 2000), is that they permit only three strip crossings for such stars, since core oxygen ignition occurs prior to a separate shell helium burning phase.

In all cases the evolution of stars through the Cepheid instability strip should be associated with gradual changes in overall dimensions and hence periods of pulsation: the period increases for evolution toward the cool edge of the instability strip as the stellar radius grows, and it decreases for evolution toward the hot edge as the stellar radius decreases. The observed parabolic trends in Cepheid $O - C$ diagrams (plots of the differences between observed times of light maximum and those computed from a linear ephemeris) have been recognized for the past half-century as evidence of the evolution of such stars through the instability strip (Parenago 1958; Struve 1959; Erlekska & Irkaev 1982). As noted by Struve (1959), “It appears that studies of period change are by far the most sensitive test available to the astronomer for detecting minute alterations in the physical characteristics of a star.”

Observations of period changes in Cepheids have been matched with some confidence to evolutionary models of massive stars in various crossings of the instability strip (e.g., Turner 1998; Turner & Berdnikov 2001, 2004) in order to identify the direction of strip crossing for individual variables. When used for such purposes, the study of Cepheid period changes becomes an important tool for the characterization of individual members of the class.

In principle, it should also be possible to use the rate of period change for individual Cepheids to establish the likely location of the object within the instability strip. Because strip crossings for individual Cepheids occur at different rates and at different luminosities for specific stellar masses, the observed rates of period change must be closely related to the strip-crossing mode and location within the instability strip. Potential constraints are imposed by variations in chemical composition and pulsation mode, e.g., fundamental mode and first overtone (Berdnikov et al. 1997; Turner et al. 1999), as well as by our limited ability to establish small rates of period change for $O - C$ data containing sizable observational uncertainties (Szabados 1983). In this paper we demonstrate the link in more detail.
2. BASIS OF THE RELATIONSHIP

The link between rate of period change in Cepheids and location within the instability strip is illustrated with the aid of Figure 1. The diagram is a theoretical H-R diagram that depicts the location of the Cepheid instability strip according to the parameters derived for Milky Way Cepheids (Turner 2001), along with Geneva evolutionary tracks for stars of 4, 5, 7, and 10 $M_{\odot}$ at $Z = 0.008$ from Lejeune & Schaerer (2001). Lines of constant stellar radius are shown crossing various portions of the instability strip. According to the well-established Cepheid period-radius relation, they should represent lines of constant pulsation period for individual Cepheids.

From an examination of Figure 1, it is clear that if one considers only Cepheids of a specific period and in a common crossing of the instability strip, those on the hot edge of the strip must be $\sim 20\%$ more massive than those on the cool edge of the strip. Since rate of evolution increases in proportion to the mass of a star, Cepheids lying on the hot edge of the strip are evolving faster, and hence changing their pulsation periods at a more rapid rate, than Cepheids of identical period lying on the cool edge of the strip. Rate of period change therefore relates directly to location within the instability strip for individual Cepheids. Differences in strip-crossing modes are only a minor concern. Cepheids with increasing periods must be in the first, third, or fifth crossing of the strip, whereas Cepheids with decreasing periods must be in the second or fourth crossing of the strip.

A minor complication arises from restrictions on our ability to identify period changes in Cepheids tied solely to stellar evolution. Some Cepheids exhibit erratic period changes that appear to originate from random fluctuations in pulsation period. SZ Tau (Berdnikov & Pastukhova 1995), S Vul (Berdnikov 1994), and V1496 Aql (Berdnikov et al. 2004) are excellent examples, although in the first two cases it is possible to identify the underlying evolutionary modifications to the pulsation period.

A study by Berdnikov & Ignatova (2000) may give the impression that stellar evolution has only a minor effect on Cepheid $O - C$ diagrams, since it notes that parabolic trends were detected in only 67 of 230 Cepheids surveyed. That number is misleading, however, given that a previous survey by Turner (1998) found parabolic trends in 137 Cepheids from a much smaller sample. The number cited by Berdnikov & Ignatova (2000) was actually intended to indicate the poor temporal coverage and lack of extensive $O - C$ data available for many well-studied Galactic Cepheids, a situation that has been remedied in recent years by our ongoing program to obtain archival data on Cepheid brightness variations using the Harvard College Observatory photographic plate collection. At present, the parabolic trends in $O - C$ diagrams typical of stellar evolution are found to be extremely common. A survey by Glushkova et al. (2005) cites a typical frequency of $\sim 80\%$ in both cluster and field Cepheids, for example, although their “anomalous” objects include Cepheids such as SV Vul in which the evolutionary trend is quite distinct (Turner & Berdnikov 2004). A more realistic frequency for Milky Way Cepheids displaying evolutionary trends is in excess of $\sim 90\%$. For many of the remaining objects, the evolutionary trends may be more obvious in longer time baselines of light-curve coverage.

As also pointed out by Fernie (1990) and by Berdnikov & Turner (2004), the $O - C$ trends indicative of evolution in Cepheids need not be strictly parabolic. If the rate at which a massive star is evolving through the instability strip is not constant with time, the $O - C$ data for the associated Cepheid variable may be better described by a third- or fourth-order polynomial. The Cepheids Y Oph (Fernie 1990) and WZ Car (Berdnikov & Turner 2004) are two objects (of several hundred) where that appears to be the case. Such complications may affect the derived rates of period change, but in most cases only by small amounts. In the large majority of studies of Cepheid period changes, the derived rate of period change reflects the evolution of the star through the instability strip (see Szabados 1983).

3. STELLAR EVOLUTION PREDICTIONS

Most computational models for evolved stars are used for constructing stellar evolutionary tracks rather than testing for pulsation instability. But, as noted by Parenago (1958), it is
possible to use the basic information they provide on gradual changes in luminosity and effective temperature to predict expected rates of period change for Cepheids of different period. A starting point is the well-known period-density relation:

$$P^3/2 = \frac{PM^{1/2}}{[(4/3)\pi]^{1/2}R^{3/2}} = Q,$$

where $P$ is the pulsation period, $\rho$ is the density, $M$ is the stellar mass, $R$ is the stellar radius, and $Q$, the pulsation constant, has a small period dependence (e.g., Kraft 1961; Fernie 1967) that we assume here varies as $P^{1/8}$, based on an empirical analysis by Turner & Burke (2002). Differentiation of the period-density relation, in conjunction with the standard equation for stellar luminosity, therefore leads to the following result:

$$\frac{\dot{P}}{P} = \frac{6L}{7L} \frac{-24T}{7T}.$$

The desired quantity, the rate of period change $\dot{P}$, is obtained from tabulated differences in stellar luminosity and effective temperature as a function of age as a model star evolves through the instability strip.

For the present study we calculated values of $\dot{P}$ from the above relationship using computational stellar evolutionary models from a variety of available published sources, namely, Maeder & Meynet (1988), Alibert et al. (1999), Lejeune & Schaerer (2001), and Claret (2004). The published data were used to compute different parameters, depending on the availability of the necessary information. Alibert et al. (1999) cite parameters for stars of different mass reaching the hot and cool edges of the instability strip, so their data yield information only about rates of period change near the center of the strip. In other cases, such as Claret (2004), there is sufficient time resolution in the output parameters to track changes in pulsation period across individual instability-strip crossings. For the remaining sources (Maeder & Meynet 1988; Lejeune & Schaerer 2001), including Claret (2004), we calculated rates of period change for the intersection of the evolutionary tracks with the observationally delineated boundaries of the instability strip defined empirically by Turner (2001), which are close to those predicted by models of pulsation instability (Alibert et al. 1999), as well as for points lying within the strip boundaries. Pulsation periods were established using the period-radius relation (Turner & Burke 2002). The present results differ from those obtained earlier (Turner & Berdnikov 2001, 2003) in being tied to a larger variety of models with a greater range of metallicity, and by the inclusion of a weak period dependence for $Q$ in the period-density relation.

The computed results on rates of period change are plotted in Figure 2 for all of the accessible models. Different symbols denote the different sources. Values calculated from the models of Alibert et al. (1999) are plotted using filled circles, while others are plotted using open circles. Plus signs indicate results calculated for stars evolving through the hot and cool edges of the instability strip, with the rate of period change in general being larger on the hot edge of the instability strip, i.e., for more massive stars. Large symbols denote stars of solar metallicity, $Z = 0.02$, intermediate-sized symbols denote stars with metallicities of $Z = 0.01$ and $Z = 0.008$, and small symbols denote stars of very low metallicity, $Z = 0.001$ and $Z = 0.004$. Lines have been drawn to enclose those regions within which the results for different stellar evolutionary models appear to cluster. Sequences of points indicate models for which the time resolution was fine enough to calculate rate of period change over the entire crossing of the instability strip.

The distribution of data points in Figure 2 suggests a variety of different conclusions regarding the models. First, the different models for the rapid first crossing of the instability strip
are in very good agreement and display very little variation with metallicity. The first crossing of the strip is a rapid transition for all stars, regardless of individual differences in rotation rate, etc., and that is evident from the models. Evidently, the computational codes used for calculating the phases of shell hydrogen burning in stars, while perhaps differing in detail from one source to another, generate nearly identical results, the small variation in rate of period change at specific pulsation period arising from the finite width of the instability strip and the fact that more massive stars cross the strip at a greater luminosity and at a faster rate than less massive stars. For stars in the first crossing of the strip, a high rate of period increase at specific pulsation period corresponds to stars on the hot edge of the strip, a low rate of period increase to stars on the cool edge of the strip.

Negative period changes arise during the second crossing of the instability strip, which occurs during the blue-loop phase of stellar evolution following the onset of core helium burning. The extent of the blue loop can depend on a variety of factors (see, for example, Becker 1985; Xu & Li 2004), such as metallicity, the treatment of core overshooting, and the distribution of CNO elements throughout the star. All factors affect how far a star enters the instability strip during core helium burning and presumably affect how rapidly it evolves within the strip. Given the potentially large differences in initial conditions for such stars as main-sequence objects, for example, large variations in initial rotation rate, one might expect real stars to display large variations in how far they penetrate the Cepheid instability strip as core helium burning objects. Somewhat unexpectedly, there are also very large variations among the model stars as well.

Evidently, metallicity plays only a minor role in governing the rate at which stars traverse the instability strip. There is as much dependence on the specifics of the stellar evolutionary code used. The models of Alibert et al. (1999), for example, generate faster rates of period decrease than do other models, despite the use of common opacity tables. Models from individual sources are at least internally consistent in their predictions for stars of different masses and for stars in all portions of the second strip crossing. The rates of period decrease during individual strip crossings are also very similar to the variations predicted on the basis of mass differences; i.e., predicted variations in rate of period decrease at a specific pulsation period are generally small, except for long-period Cepheids.

The third crossing of the instability strip occurs during the late stages of core helium burning and gives rise to period increases, for which the predicted rates are depicted in the top panel of Figure 2, along with those for the first crossing. Most of the comments regarding the second crossing of the strip apply equally to the third crossing. Again, metallicity seems to play a less important role in the predicted rates of period increase than differences in the evolutionary code. The models of Alibert et al. (1999) predict faster rates of period change (period increases in this case) than do other models, although with less consistency for stars of different mass. The rates of period increase during individual strip crossings are also similar to the variations predicted on the basis of mass differences, and predicted variations in the rate of period increase at a specific pulsation period are generally small.

A well-known problem arises for low-mass stars in the second and third crossings of the instability strip, since the blue-loop phases of evolutionary models for stars of solar metallicity, \( Z = 0.02 \), do not enter the strip for \( M < 4.75 \, M_\odot \) (see Alibert et al. 1999). Model stars of lower metallicity can traverse the strip at smaller masses, but only often on the cool edge. By inference, most classical Cepheids of near-solar metallicity should have pulsation periods in excess of \( \sim 3.5 \) days (e.g., Turner 1996), consistent with the observational sample. Nearby Milky Way Cepheids have abundances close to the solar values (e.g., Andrievsky et al. 2002a, 2002b), and only a few have periods of less than 3.5 days. Many may be overtone pulsators.

The observational picture is illustrated in Figure 3, which presents available data on period changes for over 200 Cepheids, as obtained from the literature (Berdnikov & Pastukhova 1994a, 1994b, 1995; Berdnikov et al. 1997, 2003; Turner 1998; Berdnikov & Ignatova 2000) and ongoing research studies by the authors (e.g., Berdnikov & Turner 2004; Berdnikov et al. 2004). The relationships plotted in Figure 3 depict the regions within which the model calculations appear to cluster.

It has been pointed out previously (e.g., Szabados 1983; Fernie 1984; Turner 1998) that the observed rates of period change in Cepheids are generally a good match to predictions from stellar evolutionary models. The data of Figure 3 provide further confirmation of that conclusion. Moreover, three further conclusions can be reached. First, once consideration is taken of the expected changes arising from evolution through the instability strip, the observed period changes in Cepheids are unlikely to contain any sizable component arising from another source. There are only a few exceptions to such a conclusion, and they are rather unusual objects such as V1496 Aql (Berdnikov et al. 2004), which exhibits period changes dominated by random fluctuations in pulsation period.

Second, the observed period changes in Cepheids deviate in small but important ways from what is expected according to predictions based on specific stellar evolutionary models. The models of Alibert et al. (1999), for example, predict faster second and third crossings of the strip than those observed, and at distinctly different rates, in contrast with the very similar observed rates of period change in Cepheids likely to be in the second and third crossings. The models of Claret (2004) are more consistent with observations in that regard, but it is necessary to have a more complete mass grid of models constructed in the same manner to make a more detailed comparison.

Third, the range in observed rates of period change for most Cepheids is smaller than that resulting from a comparison of the results from different evolutionary models. This is somewhat surprising, given our previous discussion about potentially
Fig. 3.—Observed rates of period change, along with their calculated uncertainties, for well-studied Cepheids possessing many years of \( O - C \) data. The lines show the relations depicted in Fig. 3, and the different strip crossings are identified.

wide variations in initial conditions for Cepheid predecessors. Evidently, real stars are similar enough in their internal characteristics that they evolve at fairly similar rates through the Cepheid instability strip.

The proportions of Cepheids in different crossing modes and in different period ranges in Figure 3 are also reasonably consistent with evolutionary expectations. For example, stars in the first crossing of the instability strip during shell hydrogen burning are evolving about 2 orders of magnitude faster than stars in second and third crossings, so their relative numbers should be small. The two Cepheids in Figure 3 undergoing large rates of period increase and falling in the predicted region for first crossers are Polaris (\( \alpha \) UMi) and DX Gem. We assume that both are first crossers, as was also argued for Polaris by Turner et al. (2005b). Moreover, the observed rate of period change for Polaris is now seen to be exactly what stellar evolutionary models predict for a star lying on the cool edge of the instability strip for first crossers.

The proportion of Cepheids with detectable parabolic trends in their \( O - C \) data also increases noticeably toward short pulsation periods, which is again consistent with the evolutionary expectation that the most abundant pulsators must be those evolving most slowly through the instability strip. There is a curious anomaly in the distribution of short-period Cepheids, where essentially no variables are found to have rates of period change as predicted for stars in second and third crossings of the strip at \( P \leq 3.5 \) days (log \( P \leq 0.55 \)). Such stars have progenitor masses of less than \( \sim 4 M_\odot \) (Turner 1996), where stellar evolutionary models for solar-metallicity stars predict that the evolutionary tracks for core helium burning stars should no longer enter the strip. The short-period cutoff in the observational sample is therefore consistent with expectations from stellar evolutionary models. But the existence of stars of \( P \leq 3.5 \) days with rates of period change roughly an order of magnitude faster than predicted for stars in second and third crossings of the instability strip is not. The uncertainties in the observed rates of period change in the anomalous objects are generally much too small to resolve the anomaly by invoking systematic errors in the values of \( \dot{P} \).

An additional factor that can be important for short-period Cepheids is overtone pulsation. The Cepheids in the observational sample have all been assumed to be fundamental-mode pulsators and would require a displacement of \( +0.15 \) in log \( P \) to establish their proper locations in Figure 3 if they were overtone pulsators. Yet, the application of such corrections to all of the anomalous objects does not affect their distribution significantly; most still fall outside the region of \( P \)-space predicted for stars in the second and third crossing of the instability strip. Current stellar evolutionary models are therefore unable to explain the existence of such stars, which suggests that the manner of treating the details of stellar evolution during blue-loop stages is very important (see also Xu & Li 2004). That is one area where improvements to the observational sample on Cepheid period changes can play an important role in testing the results from stellar evolutionary models.

4. \( \dot{P} \) AS A FUNDAMENTAL PARAMETER

In Figure 3 the dispersion in the rates of period change \( \dot{P} \) observed in long-period Cepheids (\( P > 10 \) days) is smaller than what is observed for the calculated dispersion in that parameter among different stellar evolutionary models. One might expect \( \dot{P} \) to correlate closely with location in the instability strip for Cepheids in all strip crossings, according to the results of Figure 1. It is informative to examine the observational data more closely to determine whether that is the case.

As a first step we note that the observed rates of Cepheid period change plotted in Figure 3 fall mainly within specific bands delineated by linear margins of slope 3.0 separated by
an order-of-magnitude range in $\dot{P}$. Figure 4 is a separate plot of the data that displays such empirically defined margins. All but two of the long-period Cepheids with increasing periods fall within the lower set of margins, as do the majority of short-period Cepheids with increasing periods. Cepheids with decreasing periods display a greater dispersion in $\dot{P}$ that may be intrinsic or may be caused by larger uncertainties in $\dot{P}$ for the stars, particularly those with small rates of period change.

The anomaly for Cepheids with $P \leq 3.5$ days ($\log P \leq 0.55$) is again apparent in Figure 4. All Cepheids of shorter period display faster rates of period change than is typical of variables populating the lower band, and there are a number of stars of longer period also falling in this region of rapid period change. Presumably the stars represent Cepheids in fourth and fifth crossings of the instability strip, with faster associated rates of period change. Multiple crossings of the instability strip appear to be possible for stars in late core helium burning stages, depending on the CNO abundances in their hydrogen-burning shells (Xu & Li 2004).

The finite range in stellar surface temperature for stars populating the instability strip at constant pulsation period implies distinct differences in pulsation efficiency that should coincide with marked differences in pulsation amplitude for Cepheids of similar period. On the hot edge of the strip the ionization zone is just beginning to reach depths where the mechanism for pulsation becomes efficient, so light amplitudes should be small but increasing with decreasing surface temperatures. On the cool edge the lower surface temperatures are associated with increased convective energy transport in the star’s outer layers (Deupree 1980), so pulsation amplitudes should also be small.

The first study of Cepheid amplitudes as a function of position in the strip by Kraft (1963) was consistent with that picture, although small-amplitude Cepheids were found only on the hot edge of the strip. All subsequent amplitude maps of the instability strip by Hofmeister (1967), Sandage & Tammann (1971), Payne-Gaposchkin (1974), Pel & Lub (1978), Turner (2001), and Sandage et al. (2004) have produced similar results, namely, a sharp rise to maximum amplitude on the hot edge of the strip followed by a more gradual decline toward the cool edge.

Cepheid amplitudes display a period dependence as well as a dependence on location within the strip, a natural consequence of an effect tied to both surface gravity and pulsation efficiency. In order to eliminate that factor in characterizing Cepheid period changes, we have normalized the resulting values of blue-light amplitude and $P$ as follows: (1) blue amplitudes $\Delta B$ were standardized through the ratio $\Delta B/\Delta B(\text{max})$, where $\Delta B(\text{max})$ is the maximum value of $\Delta B$ for the star’s pulsation period, and (2) $\dot{P}$ was adjusted to the equivalent value for a Cepheid with a pulsation period of 10 days using the empirically obtained slope plotted in Figure 4.

Figure 5 plots such data for Cepheids with 12 days $\leq P \leq$ 40 days and increasing pulsation periods ($P \approx 20$ days). The top panel of the diagram plots the individual data, while the middle panel plots running means for the data. The bottom panel is an alternate interpretation of the same data, as described below. Similar plots are given in Figure 6 for Cepheids with 4 days $\leq P \leq 8$ days and increasing pulsation periods ($P \approx 6$ days), and in Figure 7 for Cepheids with 4 days $\leq P \leq 8$ days and decreasing pulsation periods ($P \approx 6$ days). Recall that large values of $\dot{P}$ should correspond to the hot side of the instability strip, and small values to the cool side.

The data for 20 day Cepheids (Fig. 5, top) display a tendency for large-amplitude Cepheids to have rates of period increase typical of stars lying near the center of the instability strip, with smaller amplitude Cepheids falling toward the hot and cool edges (larger and smaller values of $\dot{P}$, respectively). The trend is more obvious when one plots running five-point means of the same data, as in the middle panel of Figure 5. There are
two long-period Cepheids with anomalously large values of $\dot{P}$, SZ Cas and AQ Pup, which are conceivably fifth crossers. If they are omitted from the running means and averages over smaller samples are included at the extremes of $\dot{P}$, one obtains the results in the bottom panel of Figure 5, which are typical of independent cross-sectional amplitude maps of the instability strip. The scatter in $\dot{P}$-values evident in the top panel of Figure 5 is intrinsic to the stars and is not the result of large uncertainties in the calculated values. Presumably there are intrinsic physical differences from one Cepheid to another that account for the scatter, as noted earlier. Differences in initial rotation velocity for the progenitor main-sequence stars might be the sole factor, given that they would generate sufficiently large variations in the abundances of the CNO elements throughout the star to affect the extent of the blue-loop stages (Xu & Li 2004).

The data for 6 day Cepheids with period increases (Fig. 6, top) are more complicated. It appears that the sample consists of two overlapping groups of objects, a feature that also appears in the running five-point means displayed in the middle panel of Figure 6. We assume that each group consists of Cepheids displaying an order-of-magnitude (factor of 10) variation in $\dot{P}$-values from the hot to cool edge of the instability strip, as displayed by the long-period Cepheids in Figure 5, and use the results presented in the bottom panel of Figure 5 as a template for the likely variations in relative amplitude with $\dot{P}$ for short-period Cepheids. When the two groups in Figure 6 are separated in such fashion and averages over smaller samples are included at extreme values of $\dot{P}$ for each group, one obtains the results in the bottom panel of Figure 6. The simplest explanation for the existence of two groups among the short-period Cepheids is the existence of higher strip crossings among the stars, namely, fifth crossings for Cepheids undergoing period increases.

Similar results apply to the data for 6 day Cepheids with period decreases (Fig. 7), when analyzed in similar fashion, despite the smaller sample size. The top panel of Figure 7...
The data on rates of period change for individual Cepheids used here are as yet mostly unpublished, since archival data for many objects are still being collected (e.g., Turner et al. 2005a). Estimates of $\dot{P}$ for specific Cepheids may therefore improve in accuracy and precision in future studies. Specialists interested in making use of the existing observational sample should contact the lead author for a copy of the current results compiled for this study.

5. DISCUSSION

Our intent here is to demonstrate that the rate of period change for a Cepheid is a useful parameter that permits one to characterize the variable in terms of specific evolutionary state. Information on $\dot{P}$ for a Cepheid, in conjunction with its known pulsation period and light amplitude, can be used to identify the strip-crossing mode for the object as well as its likely location within the strip, the latter independently of its observed color and reddening. The parameter $\dot{P}$ may even be useful for establishing whether a Cepheid is a fundamental-mode pulsator or an overtone pulsator, although we leave that as a future exercise.

If we interpret the results of Figures 5–7 as a generic indicator of how pulsation amplitude varies across the instability strip, then the width of the strip in $P$ at constant period, which amounts to $\sim 1.2$ in $\log P$, must encompass a range of $\sim 16$ in $\dot{P}$. Of that, an intrinsic dispersion in $\log P$–values amounting to perhaps 0.4–0.5, a factor of $\sim 3$, presumably arises from actual internal differences in the Cepheids resulting from different histories for their progenitor stars. Specific stellar evolutionary models presented in Figure 2 predict a smaller variation than what is observed, which may reflect the simplicity of the models. In that regard, observed rates of period change in Cepheids can play an important role as a check on how closely stellar evolutionary models match real stars. Until now Cepheid period changes have not been used for that purpose.

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