

Long-Term Changes in Mira Stars. II. A Search for Evolutionary Period Changes in Mira Stars

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ABSTRACT. The ($O - C$) diagrams of Mira stars are dominated by the effects of random, cycle-to-cycle fluctuations in period. Nevertheless, it is possible to average these effects over many stars with similar properties and compare the average apparent period change with that predicted by evolutionary models. The average rate of period change for a $1.0 M_{\odot}$ model, averaged over the Mira phase, is $+28 \times 10^{-6}$ days day^{-1} if the pulsation is in the fundamental mode, and $+11 \times 10^{-6}$ days day^{-1} if it is in the first overtone mode (as most Mira star pulsation is now believed to be). The observed changes are not inconsistent with these results, in the sense that (1) positive period changes outnumber negative ones and (2) the average period change of all of the M type Miras is $+16 \times 10^{-6}$ days day^{-1} ; the median value is $+14.5 \times 10^{-6}$ days day^{-1} . Of the seven M type Miras with $[V - 12 \mu\text{m}]$ colors greater than 13.5, six had positive period changes. There is some evidence that C type Miras have larger period changes than M and S types.

1. INTRODUCTION

Mira stars are pulsating red giants of late spectral type. By definition, they have visual amplitudes greater than 2.5 mag. They have periods of 100–1000 days. They are evolving through the tip of the asymptotic giant branch (AGB) in the H-R diagram on a timescale of hundreds of thousands of years and, as such, are affected by two significant processes: (1) in the interior, helium shell flashes, which cause large excursions in their luminosity and period on a timescale of tens of thousands of years, and (2) in the outer layers, pulsation-enhanced mass loss, which reduces their envelope masses, and ultimately drives them on their way to the white dwarf stage.

The period changes to be expected in Mira stars, due to evolution, can be calculated from evolutionary models such as those of Vassiliadis & Wood (1993). Earlier work by Wood & Zarro (1981) had shown that period changes can be large in certain parts of the helium shell flash cycle, and that period changes of this magnitude were observed in a few Miras (R Hya, R Aql, W Dra). In most Miras, however, the apparent period changes, as measured from ($O - C$) diagrams, are dominated by random cycle-to-cycle fluctuations (Eddington & Plakidis 1929; Sterne & Campbell 1936; Isles & Saw 1987; Lloyd 1989; Percy & Colivas 1998). Lombard & Koen (1997) have described a method for detecting (though not necessarily measuring) real period changes in cases such as these.

Kowalsky et al. (1986) determined mean periods and ($O - C$) diagrams for 391 bright Mira stars, using 75 yr of times of maximum brightness in the AAVSO international database of visual observations. Almost all of the ($O - C$) dia-

grams showed a “random walk” character, as expected from random cycle-to-cycle fluctuations in period.

2. OBSERVATIONS

This study was carried out using the 75 yr database of times and magnitudes of maximum and minimum brightness of 391 bright Mira stars, determined from visual observations by the American Association of Variable Star Observers (AAVSO) (Kowalsky et al. 1986). The accuracy of the data depends on several factors: the brightness of the star at the particular maximum or minimum, and the density of observations—which will be low if the star was near the Sun at the time. Generally, the times are accurate to 3–5 days, and the magnitudes are accurate to 0.1–0.2 mag at maximum; the accuracy may be somewhat less at minimum. In the case of the magnitudes, this is the *internal* accuracy; the magnitudes are determined relative to a sequence of comparison stars, and the adopted magnitudes of these may differ significantly from the UBV system. The adopted magnitudes, however, have been extremely stable over the 75 yr; this is one of the very positive features of AAVSO data.

3. ANALYSIS

3.1. Observations

To first order, evolutionary effects produce a linear change in period. The ($O - C$) diagram should therefore be a parabola, in the absence of errors, or other sources of period change. The ($O - C$) diagrams of Mira stars are generally not parabola, due to the random cycle-to-cycle fluctuations in period. Nev-

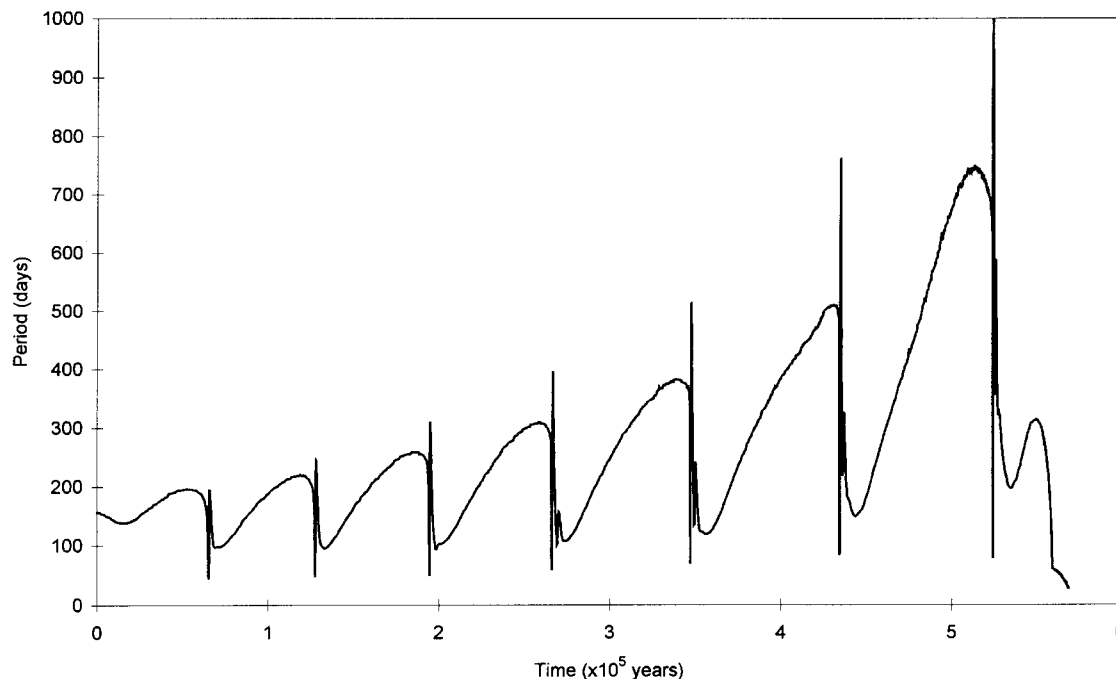


FIG. 1.—Time variation of the fundamental pulsation period of a $1.0 M_{\odot}$ model of a Mira star (Vassiliadis & Wood 1993). The long-term changes are due to the nuclear and mass-loss evolution of the star. The shorter term changes are due to helium shell flashes.

ertheless, the evolutionary effects should be present beneath the “noise.” Our approach is to fit parabolae to the ($O - C$) diagrams and then average the rates of period change over many stars with similar properties [chemical type M, S, or C (including N and R), and period] to see if the noise can be averaged out. (Alternatively, the period can be determined for each cycle, using the measured times of maximum, and the period plotted against time to determine the best estimate of the linear rate of period change. The two approaches give similar results.) This same general approach to averaging out the period noise has been successfully used on RR Lyrae stars in different globular clusters (Smith 1997).

We used the periods that had been derived by Kowalsky et al. (1986) from the same ($O - C$) diagrams, so the best straight-line fit to the ($O - C$) diagram was always a horizontal line. In addition to the rate of period change β in days day^{-1} , we derived two additional quantities: the ($O - C$) of the first and last maximum, relative to the horizontal straight line mentioned above.

The spectroscopic subtypes (M, S, or C) were taken from the fourth edition of the General Catalogue of Variable Stars (Kholopov 1985); there were 322 M types, 28 S types, and 29 C types in our sample. The 12 and 25 μm fluxes were taken from the *IRAS* Catalog (1988), converted to magnitudes, and used to determine [$V - 12 \mu\text{m}$] and [$12-25 \mu\text{m}$] colors. A few of the stars were in the parts of the sky not observed by *IRAS*.

3.2. Models

The models of Vassiliadis & Wood (1993) were kindly made available by ftp by Professor Wood. We have used these models to determine the period as a function of time. The rate of period change was determined for each increment of time. The distribution of the rate of period change was then determined for the model, during the time interval of the Mira phase. For a $1.0 M_{\odot}$ model, the relation between the fundamental mode period and time is shown in Figure 1. Note that the period change is small and positive for most of the time, but there are brief intervals when the period change is much larger—sometimes positive, and sometimes negative. This is reflected in the distribution of the values of β , described below.

We also determined the period, and the rate of change of period as a function of time, for models of 1.5, 2.0, 2.5, and $3.5 M_{\odot}$.

4. RESULTS

The values of β for a $1.0 M_{\odot}$ model were distributed as follows (Fig. 2): 4.5% more negative than 10^{-4} days day^{-1} ; 16.5% negative and between 10^{-4} and zero; 77.5% positive and between zero and 10^{-4} ; and 1.5% more positive than 10^{-4} . This result is consistent with the picture in Figure 1. The results were quite similar, both qualitatively and quantitatively, for the higher mass models. The characteristic time (P/\dot{P}) is typically about 3×10^4 yr, as expected from Figure 1.

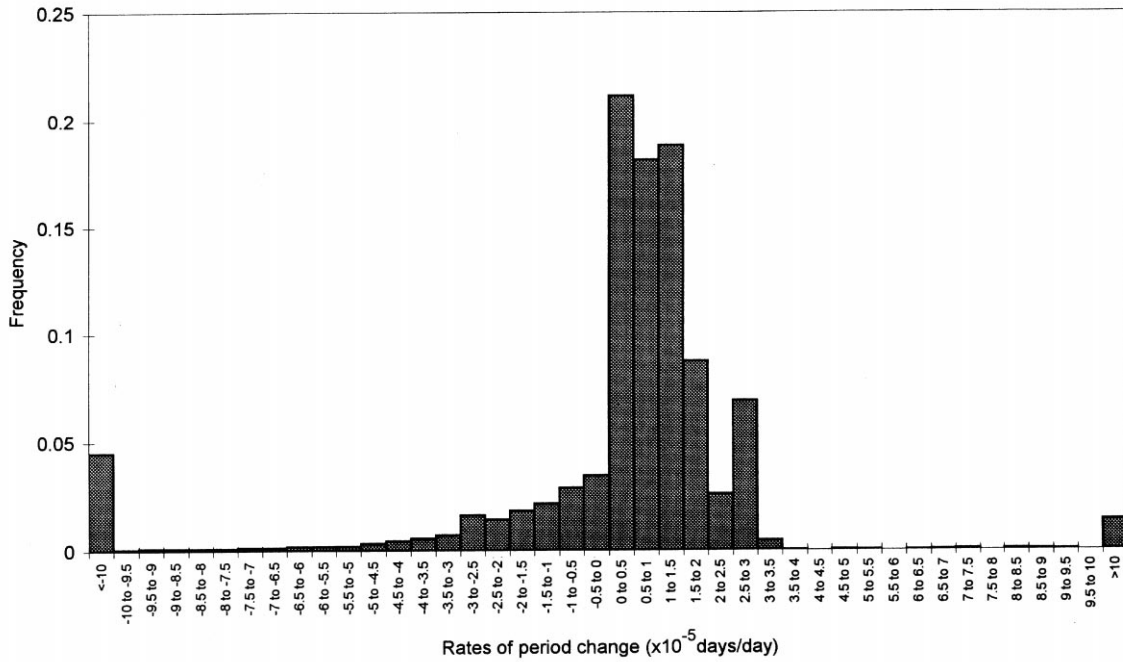


FIG. 2.—Distribution of the values of the rate of period change β (days day⁻¹) for the model shown in Fig. 1; it has solar mass and composition

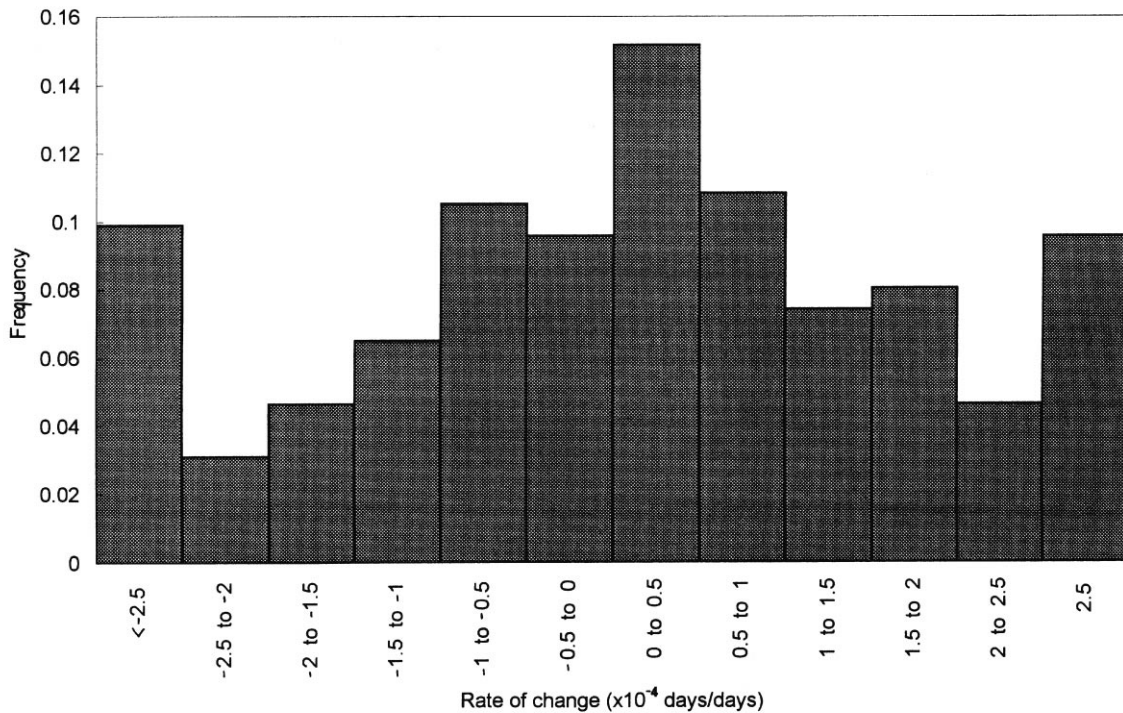


FIG. 3.—Distribution of the values of the observed rate of period change β (days day⁻¹) for the M-type Miras in the sample

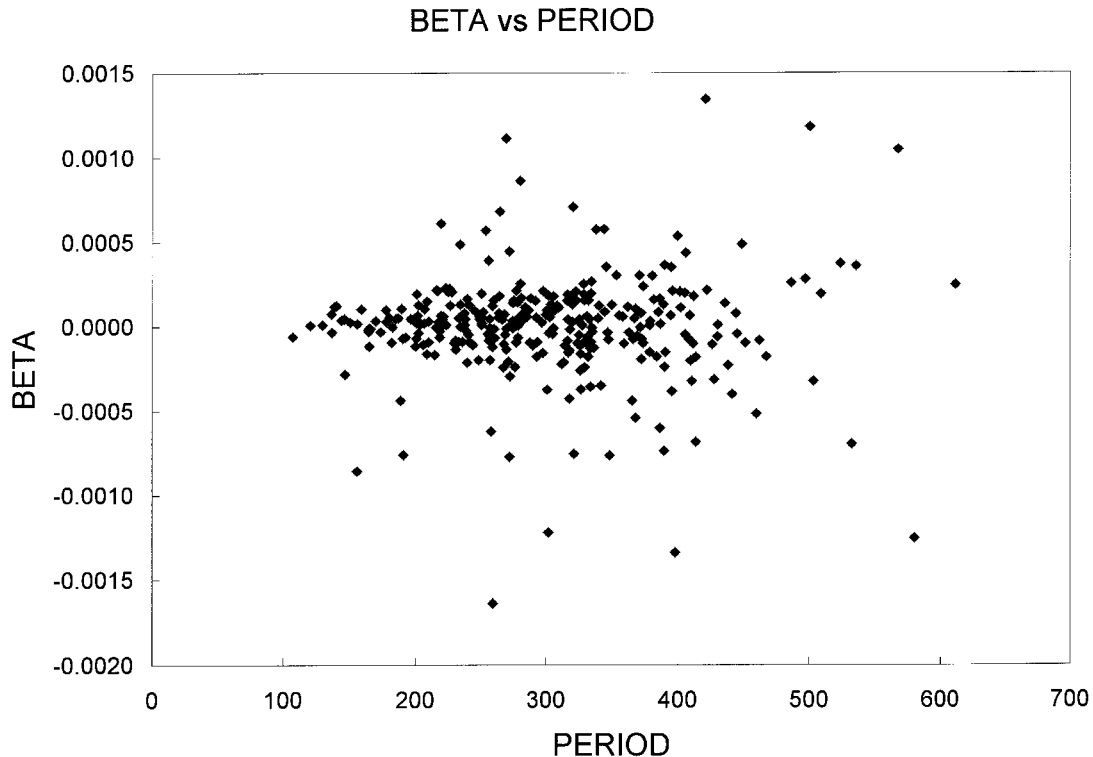


Fig. 4.—Relation between the rate of period change β (days day⁻¹) and the period for the stars in our sample

Values of β (days day⁻¹) were determined for each of the stars in the sample (Fig. 3). A list of these values can be obtained from J. R. P. They generally lie in the range $\pm 5 \times 10^{-4}$ days day⁻¹. About 55% were positive, and about 45% were negative.

Of the stars that have absolute values of $\beta > 5 \times 10^{-4}$ days day⁻¹, 17 have positive β and 20 have negative β ; the difference is probably not significant. Of the stars that have $\beta > 10^{-3}$, four have positive β (S Ori, T Cnc, RZ Cyg, and UX Cyg), and seven have negative β (W Tau, Z Tau, RU Tau, V Hya, R Hya, R Aql, and RU Vul). This difference, if it is significant, is in agreement with the models. The distributions of the values of β for M and S type Miras were similar, but the C type Miras tended to have larger absolute values of β : 37% having $\beta > 2.5 \times 10^{-4}$ days day⁻¹, as compared with 20% of M and S types. This result is suggestive, though not necessarily statistically significant. The average period fluctuations for the C type Miras were marginally larger than for the M types, which were marginally larger than for the S types, but this effect is probably not large enough to explain the differences in the values of β . The most extreme values of β were $+39.7 \times 10^{-4}$ days day⁻¹ for T Cnc, and -29.0×10^{-4} days day⁻¹ for V Hya. Both are C type Miras.

There is a general tendency for the absolute value of β to correlate with period and/or color (Figs. 4 and 5). This is not surprising, since most of the “period change” is apparent and

is caused by the random, cycle-to-cycle fluctuations, which are somewhat greater for the more extreme stars (Percy & Colivas 1998). Stars with smaller period fluctuations tended to have smaller values of β .

The values of β were binned in various ways to determine whether the random fluctuations could be averaged out to reveal a correlation between actual period change and other properties of the stars. Figures 6 and 7 show two examples. In every case, the standard errors of the mean values of β were of the same order as the mean values themselves, i.e., the mean values were not significantly different from zero. The only possible exception is the last point in Figure 7. Of the seven M type Miras with the most extreme colors, six had positive values of β . They are RR Aql, V Cam, S Cas, UX Cyg, V Cyg, RW Lyr, RV Peg, and R Vol.

The average value of β for all of the M stars in the sample was $+17 \times 10^{-6}$ days day⁻¹. The estimated standard error of this average was $\pm 10 \times 10^{-6}$ days day⁻¹. The median value of β was $+14.5 \times 10^{-6}$ days day⁻¹. The average value of the rate of change of the fundamental period of a $1.0 M_{\odot}$ model was $+29 \times 10^{-6}$ days day⁻¹.

5. DISCUSSION AND CONCLUSIONS

In the absence of observational errors, or random fluctuations in period, the ($O - C$) diagrams of Mira stars will be parabolae

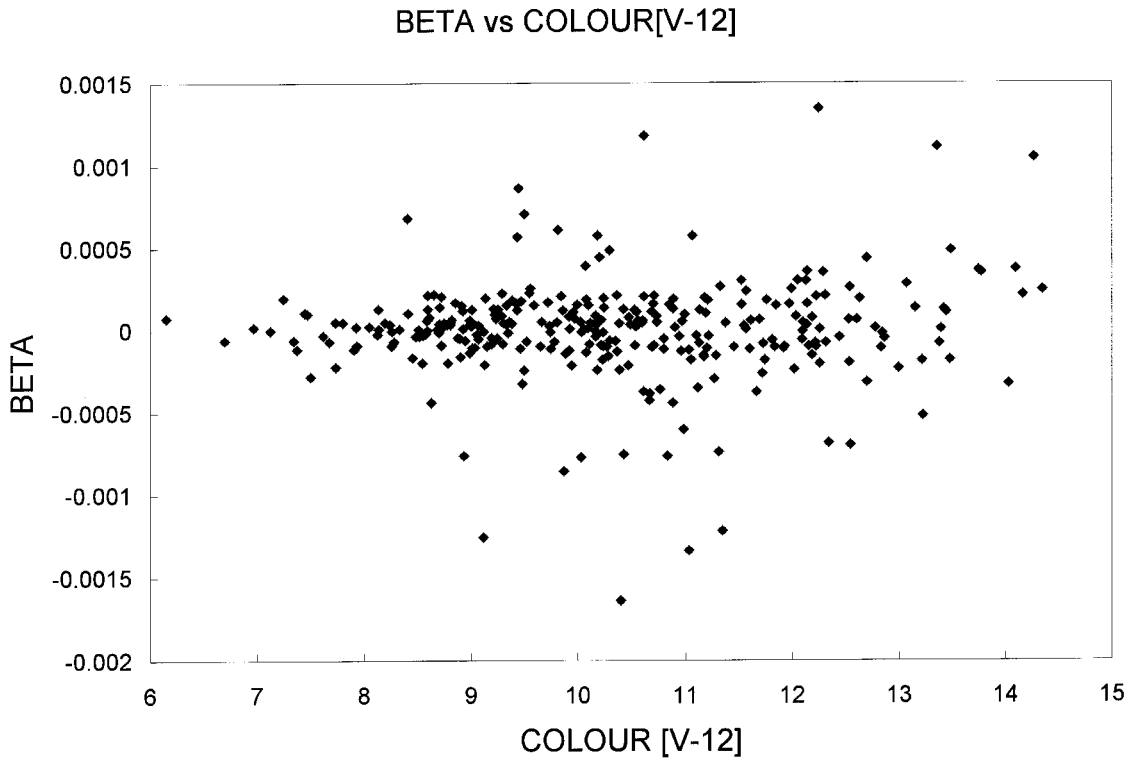


FIG. 5.—Relation between the rate of period change β (days day⁻¹) and the $[V - 12 \mu\text{m}]$ color for the stars in our sample

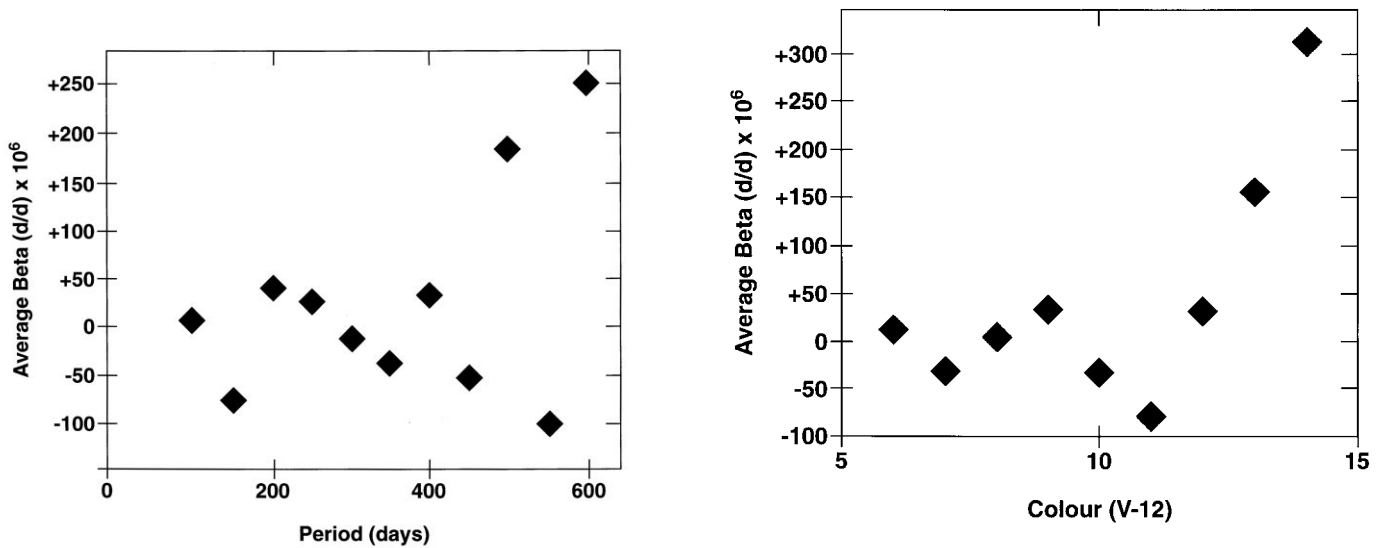


FIG. 6.—Relation between the period change β , averaged over several dozen stars, and the periods of the stars. For each point, the deviation of the mean from zero is about 1σ .

FIG. 7.—Relation between the period change β , averaged over several dozen stars, and the $[V - 12 \mu\text{m}]$ colors of the stars. For each point, the deviation of the mean from zero is about 1σ , with the exception of the last point, which is about 2σ —but based on a very small sample.

whose curvature reflects the current direction and rate of evolution of the star. The models of Vassiliadis & Wood (1993) predict the distribution of these directions and rates. Random fluctuations in period are certainly present (Eddington & Plakidis 1929; Percy & Colivas 1998), and these will mimic evolutionary changes in period.

As expected, the distribution of the observed rates of period change (Fig. 3) was much broader than the distribution of the expected rates (Fig. 2), as a result of the random fluctuations. When the observed rates were averaged in bins of similar period and chemical type (M, S, C), the average rates were zero to within their standard errors. It may be significant, however, that, of the seven reddest M type Miras, six had positive values of β . Also, C type Miras appeared to have slightly larger values of β than M and S types.

When all of the observed period changes were averaged, the value ($+17 \times 10^{-6}$ days day $^{-1}$) compared favorably with the average of the expected values ($+29 \times 10^{-6}$ days day $^{-1}$). This suggests that, beneath the random fluctuations, we are beginning to see evolutionary effects.

There is increasing evidence that most Mira stars may be pulsating in the first overtone (Barthès 1998 and references therein). If this is the case, then the expected value of the period change may be as low as $+11 \times 10^{-6}$ days day $^{-1}$, since the rate of period change scales as the period, and the first overtone period is about 0.4 times the fundamental period.

The goal of this project was to see whether the random effects could be averaged over 391 stars to reveal the actual distri-

bution of the evolutionary period changes. We believe that the excess of positive values of β , and the positive average and median values of β , indicate that we have detected the evolutionary period change in these stars. If the majority of Miras are pulsating in the first overtone, then the quantitative agreement between the expected and observed period changes is surprisingly good.

This agreement, however, is significant at less than the 2σ level. Since the precision to which period changes can be measured increases as the *square* of the elapsed time, we can hope that, in another 75 yr, we may be able to detect the expected evolutionary changes with greater confidence. The AAVSO and other groups of variable star observers have performed a unique service to the astronomical community through their long-term monitoring of Miras and other variables. Our results suggest that their observations will continue to provide new results and insights for many decades to come.

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