Period Changes in δ Scuti Stars: ρ Puppis

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Abstract Using new and published photometric observations of ρ Pup spanning sixty-two years, a period of pulsation of 0.14088143(3) day was determined. Unfortunately the value for the period of ρ Pup listed in the GCVS appears to be inconsistent with the value determined from this extensive body of data. The epoch given by Struve *et al.* (1956) at HJD 2435560.756 was chosen from existing epochs as it displays the maximum light near the middle of the magnitude-phase plot. Additionally, it was determined that any period change for ρ Pup is within $\pm 8 \times 10^{-9}$ yr $^{-1}$, although a period change arising from evolution of this star would be expected to be positive in the sense of the period lengthening.

1. Introduction

δ Scuti variables are pulsating stars lying in the lower part of the Cepheid instability strip, near the main sequence. This class of variable star is believed to comprise pre-main-sequence, main-sequence, and post-main sequence stars of mainly Population I but also including some of Population II. Templeton (2005) and Breger and Pamyatnykh (1998) have discussed period changes in δ Scuti stars in the context of stellar evolution and its underlying astrophysics. In principle, measuring such changes provides an observational test of stellar evolutionary theory, however, a number of problems have arisen:

- Period changes reported for some δ Scuti stars greatly exceed rates derived from theoretical models of stellar evolution.
- There are nearly equal numbers of negative and positive rates of period change reported, whereas current theoretical understanding predicts that the periods for radial modes increase during most of the post-main sequence stage of evolution of δ Scuti variables. Positive changes (i.e. increasing periods) should then predominate owing to a greater number of δ Scuti variables being post-main sequence stars.
- Sudden changes or “jumps” in period have been reported or inferred.
- Effects of binarity may not be readily detected or, where detected, not well determined.

Theoretical studies of stellar evolution suggest that rates of period (P) changes, (1/P)dP/dt, increase from 10^{-10} yr^{-1} for stars on the main sequence to 10^{-7} yr^{-1} for evolved δ Scuti stars. While higher rates are indicated for pre-main sequence stars, these form only a very small subset of the known δ Scuti stars. Breger and Pamyatnykh (1998) discuss the apparent discrepancy between observed period changes and those calculated to arise from stellar evolution, suggesting that other, undetermined, mechanisms may be at work. Templeton (2005) notes, however, that explanations such as observational uncertainties and analysis artifacts cannot be ruled out.

Ongoing observations of δ Scuti stars are thus needed to improve the determination of their periods of pulsation and accurately ascertain both the magnitude and sign of any period changes. ρ Pup provides an ideal candidate for such studies because:

- It has a single period of pulsation.
- For a δ Scuti star it has a relatively large amplitude (ΔV > 0.1 magnitude).
- There is strong evidence that it exhibits only radial pulsation, as its radial velocity curve follows a sinusoid predicted from simple radial pulsation theory (Campos and Smith 1980).
- As one of the first five of this class of variable to be identified and measured (Baglin *et al.* 1973), there are photometric observations extending back over sixty years to 1946 and radial velocity measurements over 110 years to 1897. This provides a long baseline for accurate determination of its period.

There are, however, drawbacks to the ongoing monitoring of the light variations of this star:

- It is a third magnitude star and hence best suited to measurement through a small-aperture telescope but, being a δ Scuti star, photoelectric techniques are required for accurate measurement of its light variations.
- It is best observed from southern latitudes where there are, unfortunately, fewer observers available to monitor such stars.

Furthermore, analysis of the light variations is hampered by the incongruities between the various epochs and periods reported—particularly between the current listing in the *General Catalogue of Variable Stars* (GCVS4; Samus *et al.* 2004) and earlier sources.

Using new photometric measurements of ρ Pup taken in 2008, previously unpublished photometric measurements by one of the authors from 1983, and the following published photometric measurements:

- Hipparcos collected between 1990 and 1993,
- Tycho collected between 1990 and 1993,
- Cape Observatory reported in 1953,
- Eggen reported in 1956,
- Ponsen reported in 1963 (includes measurements with Walraven),
- Doss reported in 1969,
- Bessell reported in 1969, and
- Dravins *et al.* reported in 1977,

a comprehensive analysis was undertaken to establish a suitable epoch, determine a best estimate of period, and look for evidence of a period change.

2. Published data

The variations in brightness of ρ Pup came to notice when they were reported by Eggen (1956), who noted that its light variations had been independently discovered at the Cape Observatory in South Africa (Cape 1953). While Eggen's measurements were in the photoelectric Johnson *V* band, the earlier Cape Observatory measurements were made in the photographic m_{pg} band. From his data Eggen determined the period to be approximately 0.141 day. Using radial velocity measurements Struve *et al.* (1956) derived a period of 0.1409 day, setting as an epoch the time of *maximum* velocity at HJD 2435560.756. Later Buscombe (1957) analyzed all radial velocity measurements available to him and claimed that a period of 0.14088143 day fitted the data with an uncertainty of 10^{-8} day.

Ponsen (1963) undertook an extensive analysis of ρ Pup which included new "blue-filter" photometric measurements, five-color photometry taken in the Walraven system, the earlier photoelectric measurements by Eggen (1956), magnitudes determined photographically (Cape 1953), and the various radial velocity measurements made between 1897 and 1956. Using the radial velocity data alone, he derived a period of 0.14088141(6) day and an epoch of HJD 2435561.672(6) which corresponded to an instance of *minimum* radial velocity. Ponsen also noted that the period he had determined from radial velocity measurements was practically identical to that used by Cousins to compute the phases for the Cape data (0.1408814 day). The value determined by Buscombe (1957) also agreed with both of these to within Ponsen's standard error of $\pm 6 \times 10^{-8}$ day.

Bessell (1969) undertook spectrophotometric measurements of ρ Pup at wavelengths between 339 and 1,040 nm. The data are presented in his Table 1 with magnitudes as a function of phase for each wavelength. Phases were calculated using the epoch given by Struve *et al.* (1956) and the period as determined by Buscombe (1957). The epochs of Buscombe and Ponsen thus differ by only 6½ cycles but, more importantly, in the sense that one relates to the maximum of the radial velocity curve and the other to its minimum.

The current values for the epoch (HJD 2444995.905) and period (0.1408809 day) of ρ Pup given in the GCVS4 (Samus *et al.* 2004) are attributed to a paper by Fracassini *et al.* (1983). They are, however, not consistent with earlier values, for example, values that were derived by Ponsen (1963) and Buscombe (1957). Fracassini *et al.* (1983) evaluated their epoch and period for ρ Pup from a least-squares solution for the epochs given by Ponsen (1963), and later observations of maxima by Trodahl and Sullivan (1977) and Dravins *et al.* (1977). Trodahl and Sullivan (1977) note in their paper that the observing conditions were unfavorable at the time of measurement of ρ Pup, that it was only observed from the Carter Observatory *"where rapidly changing weather patterns can lead to systematic errors in the measured color indices,"* and that a different comparison star was used for measurements on the second night. Additionally, their published paper includes the data only as a course-grain plot of magnitude versus time, where the time was measured relative to local midnight. Heliocentric corrections are thus not applied and no epoch is listed. Consequently, Trodahl and Sullivan's data could not be included in our analysis.

Dravins *et al.* (1977) give a plot of Strömgren *v*- and *y*-band magnitudes and *b–y* color index as a function of HJD. In a following table they list the epochs for the *v*, *b*, and *y* bands along with other quantities for ρ Pup, but it should be noted that the epochs listed relate to the *maximum numerical* values of the quantities tabulated, which in the case of the *v*- and *y*-band measurements correspond to *minimum* brightness. Also, they report differences in the epochs of the maxima observed in the *v*, *b*, and *y* bands but these differences amount to a little more than two minutes. Such a difference may then be viewed in the context of the description of their observing procedure where they note that the *"integration time for each filter was ≈ 10s and the interval between successive sets of* ρ *Pup observations ≈ 6m."* Dravins *et al.* (1977) also mention photometric observations by Doss (1969). This work, published as a *Kodaikanal Observatory Bulletin*, was not referenced in any of the other papers used in our analysis of ρ Pup. Although the paper is somewhat obscure, a scanned copy was eventually located via an Internet search. Some significant discrepancies in the paper were noted, such as an incorrect value given for Ponsen's published epoch for his photometric measurements (which the author apparently uses in their calculations), the mixing of the epoch from Ponsen's photometric measurements with the period he gives for the radial velocity measurements, and no mention of the comparison star to which the values of Δm listed in his Table 1 are relative. Noting the two comparison stars used, we inferred from the size of values of Δm listed that they represent differences in magnitude between 11 Pup (HR 3102) and ρ Pup, hence a suitable dataset of Johnson *B* or *V* magnitude versus HJD could be reconstructed.

While Fracassini *et al.* (1983) include computed maxima for the fluxes they measured from UV high-resolution spectra of ρ Pup they note that these maxima "*must be considered with great caution owing to the interval of time between the exposures (≈30m–40m), too long in comparison with the pulsation period of the star, and the poor number of point[s].*" Thus, the maxima they evaluated have not been included in the current analysis.

Hipparcos H_p and Tycho V_T magnitudes (as a function of heliocentric Julian Date) for ρ Pup were downloaded from the Hipparcos and Tycho catalogues (ESA 1997). Access to these catalogues was through the VIZIER database (Ochsenbein *et al.* 2000). The Hipparcos data downloaded span the time interval from 7 January 1990 to 25 February 1993, and the Tycho data from 7 January 1990 to 24 February 1993.

3. Unpublished data

Photometry of ρ Pup had previously been undertaken by one of the authors (Moon) on 19 April, 11 May, and 18–20 May 1983, but remained unpublished. The resulting measured *V* magnitudes, forty-seven in all, were calculated using the same comparison star as used by Eggen (1956), i.e., ξ Pup. For this analysis data reduction was undertaken afresh with corrections applied for atmospheric extinction (evaluated for each night from the comparison star). The magnitudes obtained were then transformed to the Johnson *V* band using the transformation coefficient determined in June 1983. Twenty-eight further measurements of ρ Pup were made on 15 February 2008 by one of the authors (Moon). For these data, HR 3102 was used as the comparison star and HR 3131 as the check star, the comparison and check stars being, respectively, about 0.3 magnitude redder and bluer in *B–V* than ρ Pup. Average *V* magnitudes for these two datasets (separated by almost twenty-four years) differed by 0.02. This may be accounted for by uncertainties arising from multiplying the rather large transformation coefficient (0.10) used for the 1983 data with a color difference between ξ Pup and ρ Pup of *B–V*=0.82. As the analysis undertaken focused on times of maxima, and the data were to be combined with data from other sources that were in other photometric bands, no adjustment was made to the 1983 magnitudes to bring the average of the two sets of data into agreement. The seventy-five new measurements are presented as two distinct datasets in Table 1.

The photometric data on ρ Pup used in this analysis thus represent a comprehensive, and perhaps exhaustive, dataset comprising approximately 1,800 measurements and spanning more than sixty years.

4. Analysis

The ρ Pup photometric data assembled by the authors are a heterogeneous dataset as they comprise measurements made with different photometric systems. As the analysis focused on selecting a suitable epoch and then evaluating an accurate period through determining the times of maxima of the light curve, the various measurements of magnitude were left in their original systems rather than attempting to apply corrections to bring their average values and ranges of light variation into alignment. This also facilitated the display of the results through a natural separation of the different datasets on the plot of magnitude as a function of phase. The particulars of the photometric bands for the datasets used in the analysis are given in Table 2.

4.1. Choice of epoch

For pulsating stars the time of maximum light coincides only approximately with that of minimum radial velocity; in the case of δ Scuti stars the minimum velocity lags approximately 1/10 of a period behind maximum light. Also there are small variations in color which are in phase with the variations in light (Percy 2007). The choice of epoch is thus somewhat problematic, as an epoch conveniently chosen to display radial velocity variations may not be the best for displaying the light variations. The earliest published photoelectric measurements with an accompanying epoch are those by Eggen (1956) spanning one week in March 1956. Ponsen (1963) noted that Eggen's data were discordant with all the other data available to him (the difference amounting to 40 minutes) but remarked that it was not clear how this should be explained. Using the adjustment of –40 minutes applied by Ponsen, Eggen's data were found to then be in agreement with all other data analyzed here. While the epoch used by Struve *et al.* (1957) is only about one day earlier than that of Ponsen, it corresponds to a maximum in radial velocity, hence, for photometric measurements, maximum light occurs near the middle of the phase plot. This epoch was also used by Bessell (1969) for his analysis. It was thus chosen as the most suitable existing epoch for analysis of the assembled photometric datasets.

4.2. Determination of the period

Values for the period of ρ Pup given by Buscombe (1957) and Cousins (see Ponsen 1963) are in agreement with that of Ponsen (1963) to within his standard error. Ponsen's period was thus chosen as the starting point for our analysis. The resulting plot of magnitude as a function of phase for the various datasets is displayed in Figure 1. Here an error of ± 0.05 magnitude is adopted for Cape Observatory photographic magnitudes (Budding and Demircan 2007). Errors are not plotted for the photoelectric measurements as they are within ± 0.01 magnitude.

There is good agreement in times of maxima for these datasets (spanning sixty-two years) to within the precision to which the maxima can be readily determined. Maximum light occurs at a Phase of about 0.4 relative to the time of maximum radial velocity. This is consistent with the expected lag of approximately 1/10 of a period between the maximum of the light variations and the minimum of the radial velocity.

Polynomial fits were made to the nine photoelectric datasets to estimate the phases of the maxima. (The Cape photographic measurements with their large errors, and the maximum and minimum observed by Dravin *et al.*, where the maximum was estimated from the epoch given for minimum light measured in the *y* band, were not used.) The phase of the predicted maxima for each dataset was then plotted as a function of its average cycle number. The resulting plot did not display any trend that could be interpreted as a period change. Incremental changes to the period, within the range of the error given by Ponsen, changed the slope of a straight line fitted (via linear regression) to the predicted maximum phase versus average cycle number for the nine photoelectric datasets. The point where the slope changed from positive to negative (and was closest to zero when using increments of 1×10^{-8}) corresponded to a period of 0.14088143 day.

The plot of resulting phase of maximum brightness versus cycle number is shown in Figure 2. For this best estimate of period the scatter in the calculated phases was ± 0.03 of a period corresponding to six minutes, which is on the order of the typical resolution in time (and arises from the time between consecutive measurements of a star when undertaking differential photometry). This gives an estimate of 3×10^{-8} day for the uncertainty in the period determined above. Changing the period by a quantity larger than Ponsen's standard error led to the datasets being no longer aligned.

4.3. Upper limit to evolutionary period changes for ρ Pup

Between the start of Eggen's measurements and those taken in 2008 by Moon, 18,959 days had elapsed (corresponding to 134,574 cycles). The magnitude of the error in the period as determined above would then correspond to a difference of 0.004 day (approximately six minutes) over this 52-year interval. Using the equation given by Breger and Pamyatnykh (1998) such an error puts an upper limit on the magnitude of the period change of 8×10^{-9} yr^{-1}, a value consistent with the range calculated from stellar evolutionary theory.

5. Conclusions

The singly-periodic pulsation of ρ Pup appears to be stable over the more than sixty years for which photometric data exist. Using a comprehensive dataset, comprising approximately 1,800 photoelectric measurements and spanning fifty-two years, the period was determined to be 0.14088143(3) day.

From the estimated error in the period it was calculated that any change in the period of pulsation of ρ Pup is within ± 8 × 10^{-9} yr^{-1}, although a measured change would be expected to be positive in the sense of the period lengthening. Such an upper limit to the observed rate of period change appears consistent with current theory.

The epoch of Struve *et al.* at HJD 2435560.756, which is based on a maximum in the radial velocity variations, appears to be the best choice of existing epochs for displaying photometric observations as it gives a maximum near the middle of the phase plot. The maximum brightness in the Johnson *V* band at HJD 2454512.0387 is well defined and may provide a more recent epoch for future measurements of this star. While ρ Pup remains a suitable candidate for searching for period changes arising from stellar evolution, the time taken to cycle between consecutive measurements now limits the precision with which times of maxima, and subsequently changes in period, can be determined. Techniques that reduce the cycle time between measurements should be developed.

It is recommended that HR 3102 and HR 3131 be used as comparison and check stars rather than ξ Pup for any future photometric measurements as their *B–V* indices straddle that of ρ Pup, being about 0.3 magnitude redder and bluer, respectively. Neither star is listed as variable in the GCVS4.

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Table 1a. Measurements of ρ Pup taken in 1983.

HJD	*V*	*HJD*	*V*	*HJD*	*V*
2445444.009	2.838	2445472.984	2.792	2445474.965	2.794
2445444.011	2.837	2445472.986	2.800	2445474.967	2.803
2445444.012	2.836	2445473.932	2.738	2445474.968	2.798
2445444.013	2.835	2445473.934	2.732	2445474.971	2.798
2445444.015	2.834	2445473.935	2.734	2445474.972	2.801
2445466.008	2.795	2445473.938	2.734	2445474.974	2.800
2445466.012	2.791	2445473.939	2.728	2445474.977	2.810
2445466.016	2.784	2445473.943	2.734	2445474.978	2.812
2445472.967	2.759	2445473.944	2.731	2445474.979	2.809
2445472.973	2.760	2445473.945	2.732	2445474.990	2.808
2445472.973	2.772	2445473.947	2.738	2445474.992	2.813
2445472.975	2.776	2445473.960	2.762	2445474.993	2.813
2445472.976	2.772	2445473.961	2.762	2445474.995	2.816
2445472.979	2.782	2445473.963	2.769	2445474.996	2.815
2445472.980	2.785	2445474.963	2.791	2445474.997	2.816
2445472.982	2.793	2445474.964	2.795		

Table 1b. Measurements of ρ Pup taken in 2008.

HJD	*V*	*HJD*	*V*	*HJD*	*V*
2454511.969	2.858	2454512.026	2.765	2454512.071	2.811
2454511.977	2.855	2454512.032	2.762	2454512.076	2.807
2454511.982	2.847	2454512.036	2.759	2454512.084	2.827
2454511.989	2.839	2454512.042	2.761	2454512.088	2.831
2454511.996	2.823	2454512.045	2.760	2454512.094	2.834
2454512.002	2.823	2454512.048	2.757	2454512.098	2.838
2454512.007	2.815	2454512.055	2.776	2454512.103	2.850
2454512.014	2.797	2454512.058	2.783	2454512.107	2.858
2454512.019	2.787	2454512.064	2.794		
2454512.023	2.781	2454512.068	2.802		

Table 2. Particulars of photometric bands of datasets used in analysis.

Photometric Band	*Effective Wavelength (nm)*	*FWHM (nm)*	*References*
Cape Photographic (m_{pg})	425	?	Allen (1973)
Johnson *V*	550	89	Allen (1973)
Johnson *B*	440	98	Allen (1973)
Ponsen “blue” filter	> 425	?	Ponsen (1963)
Walraven *V*	544	71	Mermilliod *et al.* (1997)
Bessell (1/λ = 1.8)	560	5	Bessell (1969)
Strömgren *y*	547	23	Mermilliod *et al.* (1997)
Hipparcos H_p	480	230	Bessell (2000)
Tycho V_T	510	105	Bessell (2000)

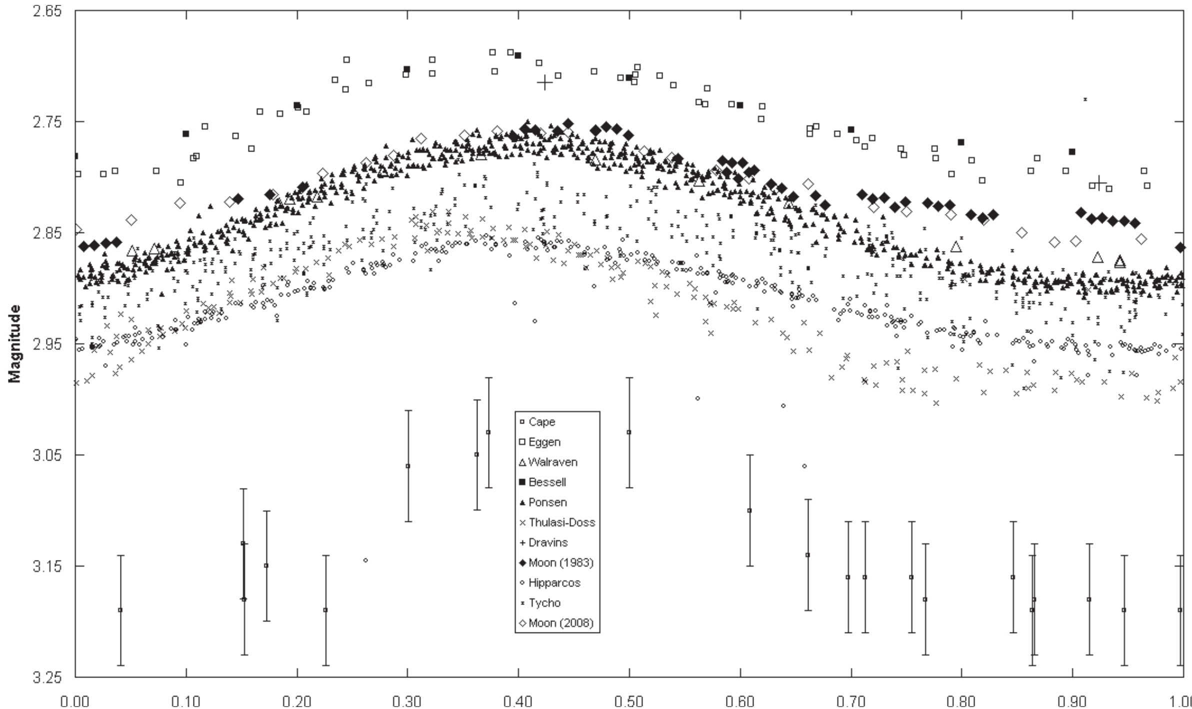

Figure 1. Measured magnitudes of ρ Pup as function of phase using an epoch of HJD 2435560.756 and a period of 0.14088141 day. Eggen's data have been corrected by –40 minutes as determined by Ponsen (1963). The typical error for a photoelectric measurement is ± 0.01 magnitude. For the photographic measurements a typical error is ± 0.05 magnitude as shown for the Cape data.

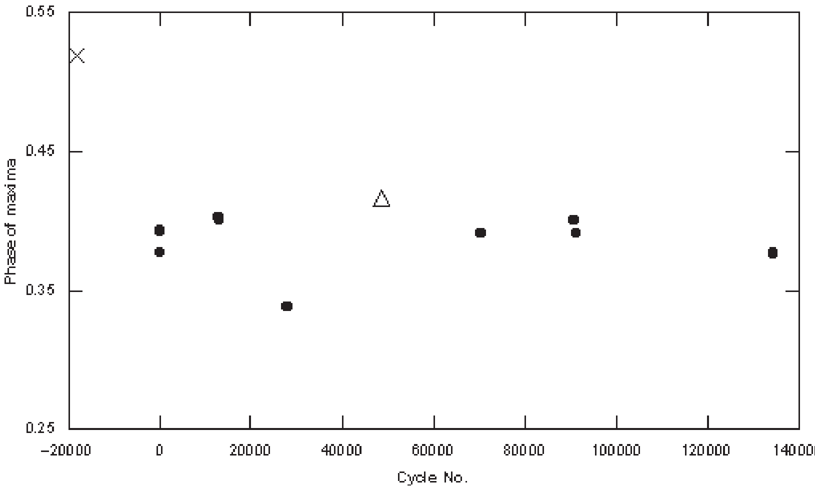

Figure 2. Phase of predicted maximum brightness as a function of average cycle number for nine photoelectric datasets (using an epoch of HJD 2435560.756 and a period of 0.14088143 day). For completeness the phases for the photographic Cape data (cross) and the maximum given by Dravins *et al.* (triangle) are included although they were not used in the analysis.