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PRE-DISCOVERY PHOTOMETRY OF THE γ DORADUS-TYPE PULSATING STAR HR 8330 (= HD 207223)

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Recently Kaye et al. (1999) presented B, V photometry and spectroscopy of HR 8330 (HD 207223; $V = 6\overset{\mathrm{m}}{.}18$; $B - V = +0.37$; F2 V-IV) that show it to be a γ Doradus-type pulsating variable star. The photometry was carried out during 1997/98 and shows that HR 8330 to have phased, low amplitude sinusoidal light and radial velocity variations with a period of $P \sim 2\overset{\mathrm{d}}{.}6$. As discussed by Kaye et al. (1999) and references therein, γ Dor stars are a newly discovered class of generally young $\sim$ F0-2 V to V-IV stars having periods that range from $0\overset{\mathrm{d}}{.}4$ to 3^{d}. These stars are generally characterized by low amplitude light variations ($< 0\overset{\mathrm{m}}{.}03$ in V) and small radial velocity variations of several $\mathrm{km\,s^{-1}}$. So far about a dozen stars have been identified as bona-fide γ Dor variables, along with an additional number of suspected members of this class. The exact nature of the pulsations in these stars is not well understood but they are thought to be due to photospheric non-radial pulsations (NRP). The simultaneous photometry and high dispersion spectroscopy carried out by Kaye et al. (1999) strongly suggests, at least for HR 8330, that non-radial g-mode pulsation is the cause of the observed periodic light and radial velocity variations.

Our photometry of HR 8330 was carried out over two intervals in 1995. Most of the observations were made on 26 nights between 29 May–5 July, 1995. Six nights of additional photometry were obtained from 26 September to 2 December, 1995. HR 8330 was not the primary target of this study but was originally used as a check star for the photometric study of the young, spotted solar-type star HN Peg. The differential photoelectric photometry was made using the 0.75-m Four College Automatic Photoelectric Telescope (located in southern Arizona) and a set of filters closely matched to the Strömgren *uvby* photometric system. The usual observing pattern of *sky–comparison–check–variable–comparison–sky* was employed. 13 Peg (HD 207652; F2 IV; $V \approx 5\overset{\mathrm{m}}{.}32$; $B - V = +0.37$) served as the primary comparison star. Several Strömgren standards were also observed on most nights.

The stars were observed with integration times of 10 seconds for about 25 minutes per night. Typically two independent measures of HR 8330 were obtained each night. The observations were reduced in the usual way and the delta-magnitudes were corrected for differential atmospheric extinction and recorded times were converted to Heliocentric Julian Day Number. About 55–60 differential measures of HR 8330 were obtained in each bandpass. The differential photometry of HR 8330 relative to 13 Peg indicated somewhat larger than expected scatter ($\sim \pm 0\overset{\mathrm{m}}{.}015$) in the measured deltamags. However, a closer

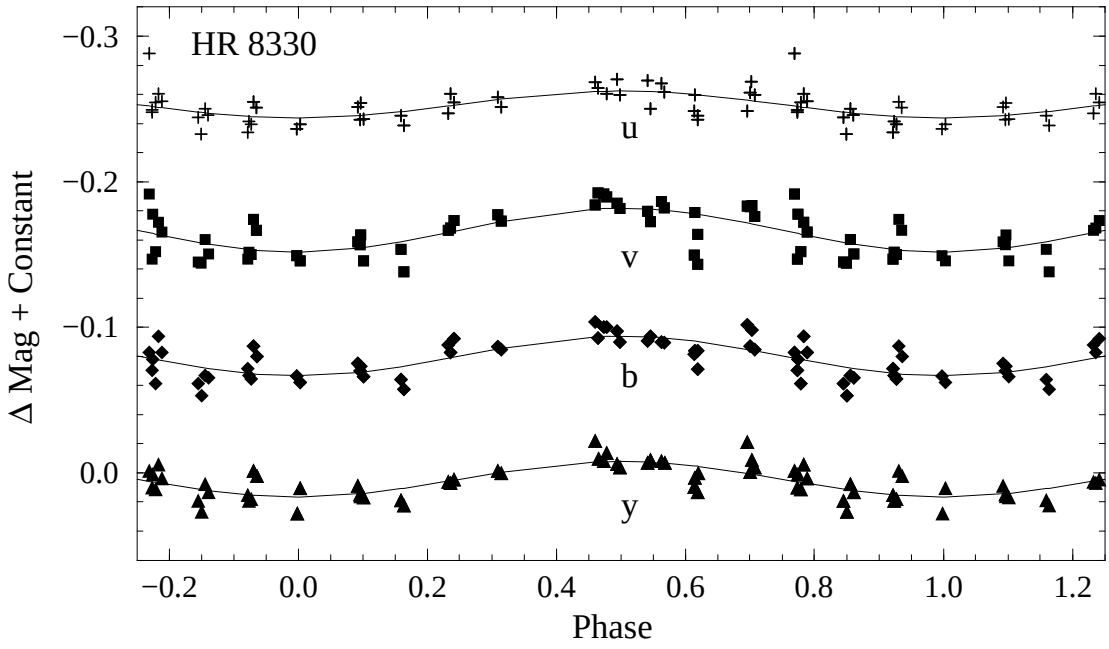

Figure 1. The differential *uvby* observations of HR 8330 are plotted against pulsation phase using the period of $P = 2\overset{d}{.}59396$. Phase 0.0 is adjusted to occur at brightness minimum. The curves plotted among the observations are least squares Fourier fits to the data sets.

scrutiny of the photometry using several constant standard stars revealed that HR 8330 has small ($0\overset{m}{.}02$–$0\overset{m}{.}03$) light variations and that 13 Peg (at least over the interval of our observations) was constant in brightness to < 8 mmags. The apparent constant nature of 13 Peg indicated by our limited photometry is supported by Hipparcos photometry which lists values of $\sigma_{\rm Hip} = 0\overset{m}{.}0007$ and Hipparcos "scatter" measure of 6 mmags.

It should be noted, however, that 13 Peg may not be an ideal comparison star because it is an astrometric binary (COU 14; $P = 26.1$ yr; $a = 0''.366$ arcsec; $\delta{\rm mag}_{\rm Hip} = 1\overset{m}{.}1$) in which the fainter companion has been reported to be a variable star (see Tamazian et al. 1999). Also, we note that 13 Peg is included in the New Catalog of Suspected Variable Stars (NVS 13891; Kukarkin et al. 1982). The inclusion of 13 Peg in the NCSVS is due to the assignment of $V = 6.16$ for the star from the photometry of Fernie (1976). This value is quite different from the value of $V \sim 5\overset{m}{.}32$ found from other photometric studies before or after that time. For example, from our study, and transforming y to V, we also find that $V = 5\overset{m}{.}32 \pm 0\overset{m}{.}01$ for 13 Peg. We suggest a possible solution to this apparent puzzle. It turns out that HR 8330 and 13 Peg have nearly the same declinations and have right ascensions that differ by ~ 4 min. Moreover, both stars have nearly identical spectral types and colors. However, as given above, the mean V-mag of HR 8330 is $V \sim 6\overset{m}{.}18$ and $B - V = +0.37$, which are nearly identical to the values of $V = 6\overset{m}{.}16$ and $B - V = +0.35$ reported by Fernie for 13 Peg. Thus, we tentatively suggest that the V, $B-V$, and $U-B$ values given by Fernie (1976) may be actually those of HR 8330 instead of 13 Peg. Of course, more observations are needed to resolve this problem. But for the purposes of this paper and in a separate paper on HN Peg, we consider 13 Peg as the primary comparison star. For long term studies, we do not recommend using 13 Peg as a comparison star until the problem of the possible variability of its fainter companion is fully resolved.

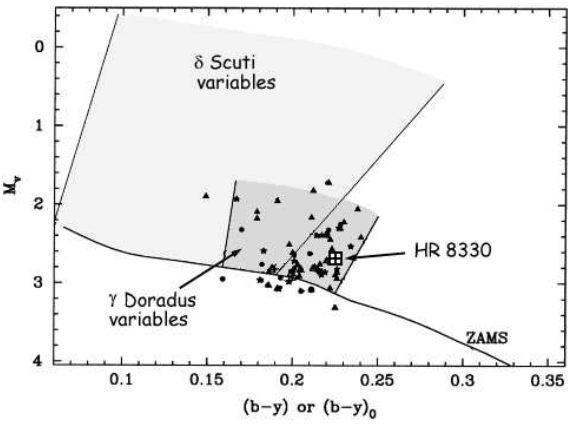

Figure 2. The location of HR 8330 in the M_v–$(b-y)$ diagram (adapted from Handler 1999) is shown along with the regions occupied by δ Scuti variables and γ Dor variables (and candidates). As shown HR 8330 is located about $0\overset{m}{.}5$ above the Zero Age Main Sequence (ZAMS), in a region where γ Dor stars are typically found

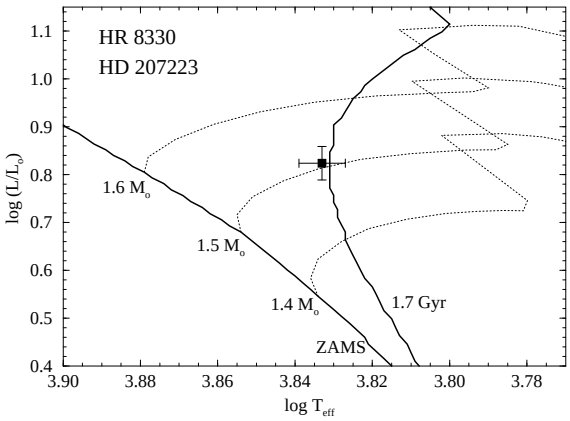

Figure 3. The location of HR 8330 in the $\log(L/L_\odot)$–$\log T_{\rm eff}$ diagram is shown. The evolution tracks from Schaller et al. (1992) are shown for $1.4M_\odot$, $1.5M_\odot$, $1.6M_\odot$ stars. The best fit of the observations to the models indicates a mass of $M \approx 1.5M_\odot$ and an evolutionary age of $\tau \approx 1.7$ Gyr

After the discovery of HR 8330 as a γ Dor-type variable by Kaye et al. (1999), we re-examined our photometry and phased the observations with their light elements:

$$T_{\rm min} = {\rm HJD}\ 2450758.440 + 2\overset{d}{.}59396 \times E.$$

The observations, plotted against phase using this ephemeris, clearly show low amplitude sinusoidal light variations similar to those published by Kaye et al. (1999). Plots of differential u, v, b, y δ-mags (HR 8330 minus 13 Peg) with least squares Fourier fits to the data sets are shown in Figure 1. The light curves were first constructed using just the May–July 1995 observations. As seen in the figure, HR 8330, unlike most other γ Dor stars, lacks a significant systematic wavelength dependence. The following are the computed light amplitudes found from least squares fits: u (Ampl. $= 0\overset{m}{.}018 \pm 0\overset{m}{.}009$), v (Ampl. $= 0\overset{m}{.}030 \pm 0\overset{m}{.}008$) b (Ampl. $= 0\overset{m}{.}028 \pm 0\overset{m}{.}006$) and y (Ampl. $= 0\overset{m}{.}024 \pm 0\overset{m}{.}005$). Several other γ Dor-type stars show multiple periods (e.g., see Zerbi et al. 1997 and Kaye and Zerbi 1997) but there is no evidence for this for HR 8330 from the 1995 or the 1997–98 observations. However, additional periods could be present but they would be difficult to detect because the brightness range for HR 8330 is relatively small and the number of observations too few.

The observations were analyzed with the Scargle-Press power spectrum program (Scargle 1982). In carrying out the period study, we used the more heavily populated May-July 1995 data subsets. Although the u, v, b, y observations were analyzed, the strongest signals of a period were found for v, b, and y data sets, so these were used to determine the period. The mean period for the 1995 observations found from the power spectrum analysis is thus: $P_{1995-{\rm ptm.}} = 2\overset{d}{.}603 \pm 0\overset{d}{.}004$. This period is very close to the mean period found by Kaye et al. (1999). We tried to improve the photometric period by adjusting the period to make the 1995 photometry phases of minimum and maximum light to agree with the 1997–98 observations. Using the light elements of Kaye et al. (1999), we found that the minimum light occurred near $(0.05 \pm 0.03)P$. The period that yielded the best fit is $P_{1995-98\ {\rm ptm.}} = 2\overset{d}{.}593464$. For future photometry of HR 8330, we recommend using the time of light minimum $T_{\rm min}$ from Kaye et al. and the above period found from a time baseline of 3 years.

The location of HR 8330 in the M_V–$(b-y)$ diagram, plotted along with the regions occupied by δ Scuti and γ Dor stars, is shown in Figure 2. This figure was adapted from Handler (1999) and the value of $M_V = +2\overset{m}{.}67 \pm 0\overset{m}{.}04$ is calculated from the Hipparcos parallax of $\pi_{Hip} = 19.9 \pm 0.8$ mas and $V = 6\overset{m}{.}18$. The value of $(b-y) = +0\overset{m}{.}226$ was obtained from SIMBAD and agrees well with our value for this index. As shown in Fig. 2, HR 8330 is located about $0\overset{m}{.}5$ above the main-sequence in a region of the M_V–$(b-y)$ diagram where γ Dor variables are typically located. The mass and evolutionary age of HR 8330 are also estimated using the stellar evolution grids of Schaller et al. (1992). From the Strömgren indices $(b-y) = +0.226$, $m1 = 0.164$, $c1 = 0.632$ and $\beta = 2.705$ from SIMBAD, and using the Strömgren photometry-$T_{\rm eff}$ calibrations of Napiwotzki (1997), values of $T_{\rm eff} = 6800 \pm 100$ K and [Fe/H] = 0.02 were obtained. Applying the small bolometric correction of BC = $0\overset{m}{.}02$ from Flower (1996), the values of $M_{Bol} = 2\overset{m}{.}69 \pm 0\overset{m}{.}04$ and $\log L/L_\odot = 0.824 \pm 0.035$ are computed. With the computed values of $\log L/L_\odot$, $\log T_{\rm eff}$, and [Fe/H] and using the evolution grids of Schaller et al. (1992), the following stellar properties were derived: $M = (1.50 \pm 0.05) M_\odot$, $\log g = 4.07 \pm 0.06$, $R = (1.87 \pm 0.25) R_\odot$, and age $(\tau) = 1.7 \pm 0.4$ Gyr. HR 8330 is plotted in Fig. 3, in the theoretical $\log L/L_\odot$ vs. $\log T_{\rm eff}$ plot from Schaller et al. (1992). The values found by us for HR 8330 are very similar to those given in Table 1 of Kaye et al. (1999). The small differences arise primarily from the differences in the Strömgren system calibrations and in the evolutionary models or relations used. As shown in the figure, HR 8330 is evolved off the main-sequence and has a mass, age and $T_{\rm eff}$ appropriate for its spectral type of F2 V-IV. Unlike a number of other γ Dor stars, which appear young, HR 8330 is evolved.

In summary, we confirm the identification of HR 8330 as a γ Dor-type variable star and give a more refined period for the star from the analysis of the 1995 and 1997–98 observations. In addition we have estimated the physical properties and evolutionary age of HR 8330. Although we find no evidence of variability of the comparison star, 13 Peg, we recommend that this star not be used as a comparison star for studying HN Peg or HR 8330 in the future. A safer choice for a comparison star is HD 209166 ($V = 5\overset{m}{.}60$; $B-V = 0.34$; F4 III). HD 209166 was used by Kaye et al. (1999) and found to be constant in brightness.

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