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V588 MON AND V589 MON, TWO DELTA SCUTI STARS IN THE DIRECTION OF NGC 2264

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RESUMEN

Se llevó a cabo fotometría fotoeléctrica tanto absoluta como diferencial de las estrellas variables de periodo corto V588 Mon (W2) y V589 Mon (W20) en la dirección del cúmulo abierto NGC 2264. De la fotometría fotoeléctrica $uvby\beta$, se estimaron las distancias y parámetros físicos de cada estrella y se presentan. La fotometría diferencial nos permitió realizar el análisis de Fourier de los datos. Las frecuencias determinadas para cada estrella son: para W2, 7.1865 c/d y para W20, 7.4385 c/d. Se discute la cuestión de su pertenencia al cúmulo.

ABSTRACT

Both differential and absolute photoelectric photometry of the short period variable stars V588 Mon (W2) and V589 Mon (W20) in the direction of the Open Cluster NGC 2264 has been carried out. From $uvby\beta$ photoelectric photometry, the distances and physical characteristics of each star have been estimated and are presented. The differential photometry of the variables allowed us to carry out a Fourier analysis of the data. The frequencies determined for each star are: for W2, 7.1865 c/d and for W20, 7.4385 c/d. The issue of cluster membership is discussed.

Key Words: **DELTA SCUTI — STARS: INDIVIDUAL (V588 MON, V589 MON)**

1. MOTIVATION

There are many advantages to studying variable stars in open clusters. For example, the parameters that determine the evolution of the stars, such as chemical composition and age can be considered to be the same for all the stars in the cluster. These data, along with the mass, effective temperature and surface gravity, allow us to better determine the physics that explain the pulsation mechanisms. The variable stars V588 Mon (W2) and V589 Mon (W20) in NGC 2264 are studied in the present paper. In particular, we are interested in solving the puzzle of why δ Scuti stars coexist with early type stars in NGC 2264.

2. OBSERVATIONS

The photometric data presented (for the variables) is of two types: differential and absolute. Both were secured at the Observatorio Astronómico Nacional, México. Different instrumentation was employed for each technique. Table 1 summarizes the observation log, as well as the instrumentation and the type of photometry used.

2.1. *Differential Photometry*

This was carried out with a one-channel photometer attached to the 84-cm telescope. The data were secured in the customary way, in which two close reference stars were considered. The sequence of observations was W2, C1, W20, and C2, with one measurement of the sky for each cycle. Each point is the average of three ten-second integrations from which one ten-second integration of the sky has been subtracted. The final values are presented as the difference of the instrumental magnitude of the star and the average of the two reference stars; the mean magnitude for the night was subtracted from the final value. In Tables 2 and 3 the photometric values in HJD versus magnitude are presented, and in Figures 1 and 2 the light curves for W2 and W20, respectively, are shown. The internal accuracies of each point, calculated by the standard deviation of the three measurements in magnitude and time are 0.002 mag and 0.0005 d, respectively.

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TABLE 1

OBSERVATION LOG

Date	JD2440000	Telescope	Filter
Dec 07, 1985	6406	150 cm	$uvby\beta$
Dec 08, 1985	6407	150 cm	$uvby\beta$
Jan 16, 1986	6446	84 cm	V
Jan 18, 1986	6448	84 cm	V
Jan 19, 1986	6449	84 cm	V

2.2. *Absolute Photometry*

Strömgren $uvby\beta$ photometry provides unique opportunities for determining both cluster membership and physical characteristics of the observed stars. Hence, we have acquired Strömgren $uvby\beta$ photometry with the Danish spectrophotometer. The description of this equipment can be found in Schuster & Nissen (1988). The data obtained were combined with a compilation of the different sources utilizing Strömgren $uvby\beta$ (Table 4). The references containing Strömgren photometry for the variables found in the literature for NGC 2264 are the following: Strom, Strom, & Yost (1971) [hereinafter SSY], Claret & Rodríguez (2000) [hereinafter CR] and those of the present paper (PP).

3. RESULTS

Very little is known of these stars, which were determined to be variables by Breger (1972). In order to fix the true nature of these stars it is indispensable to determine their periodic content. The first reliable values of period and amplitude of variation were proposed by Breger in 1972 and have remained unchallenged since then. CR assigned the periods of 0.140 and 0.1594 d for W2 and W20, respectively. With more data now available it seemed interesting to verify the constancy of pulsation of these stars. Hence, a period analysis was done.

The period determination analysis was carried out using PERIOD, the numerical package developed by Breger (1991). This method can fit and improve multiple frequencies simultaneously without prewhitening and gives as output the best frequencies, amplitudes, phases, residuals, and zero-points. The results of the periodograms are presented in Table 5 and the periodograms are shown in Figures 3 and 4. Given a time span of 43 days, only about 310 cycles of the principal period, the formal period accuracy would be about ±0.0006 c/d. There is still the risk of period misidentification due to the strong daily aliases seen in Figs. 3 and 4. However, agreement within reasonable uncertainties with the values

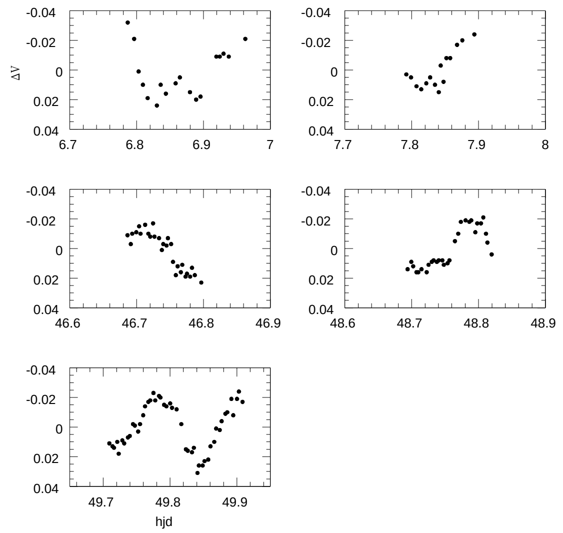

Fig. 1. Light curve of the δ Scuti star W2. HJD shown = HJD2446400.

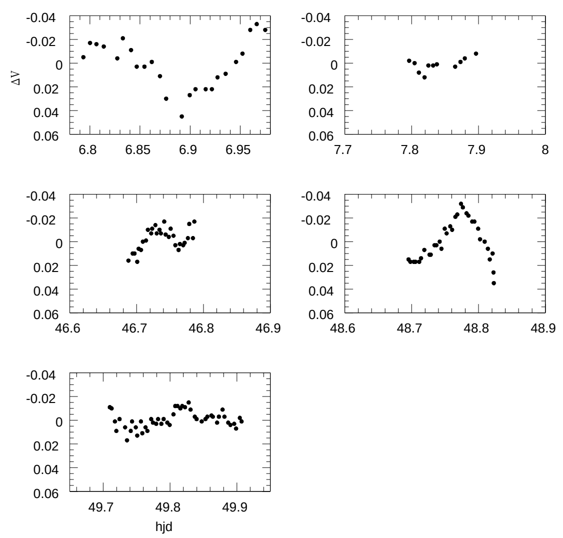

Fig. 2. Light curve of the δ Scuti star W20. HJD shown = HJD2446400.

published by CR, Rodríguez & Breger (2001), and even Breger's (1972) discovery data would suggest we have identified the correct peaks in the Fourier spectrum. There is still the possibility that all observers have misidentified aliases, since there are no simultaneous multi-site data available for these variable stars. The results, (Table 5) therefore, should be taken with caution but some significance must

TABLE 2

DIFFERENTIAL PHOTOMETRY OF THE DELTA SCUTI STAR W2 IN THE V FILTER

Time	ΔV	Time	ΔV	Time	ΔV	Time	ΔV	Time	ΔV
6.787	−0.032	7.852	−0.008	46.775	0.017	48.798	−0.017	49.795	−0.014
6.796	−0.021	7.858	−0.008	46.780	0.019	48.804	−0.017	49.800	−0.016
6.803	0.001	7.868	−0.017	46.783	0.013	48.807	−0.021	49.803	−0.013
6.809	0.010	7.876	−0.020	46.787	0.018	48.811	−0.010	49.810	−0.012
6.817	0.019	7.894	−0.024	46.797	0.023	48.813	−0.004	49.817	−0.002
6.830	0.024	46.686	−0.009	48.694	0.014	48.820	0.004	49.824	0.015
6.836	0.010	46.691	−0.003	48.699	0.009	49.709	0.011	49.827	0.016
6.844	0.016	46.693	−0.010	48.702	0.012	49.714	0.013	49.833	0.017
6.858	0.009	46.700	−0.011	48.707	0.016	49.716	0.014	49.836	0.014
6.865	0.005	46.704	−0.015	48.710	0.016	49.721	0.010	49.841	0.031
6.880	0.015	46.706	−0.010	48.715	0.014	49.723	0.018	49.843	0.026
6.889	0.020	46.713	−0.016	48.722	0.016	49.729	0.009	49.849	0.026
6.896	0.018	46.718	−0.010	48.725	0.011	49.731	0.011	49.852	0.023
6.919	−0.009	46.720	−0.008	48.730	0.009	49.737	0.007	49.857	0.022
6.924	−0.009	46.725	−0.017	48.733	0.008	49.740	0.006	49.861	0.013
6.930	−0.011	46.727	−0.008	48.738	0.009	49.745	−0.002	49.866	0.010
6.938	−0.009	46.734	−0.007	48.740	0.008	49.747	−0.001	49.869	0.001
6.963	−0.021	46.738	0.001	48.746	0.008	49.752	0.003	49.874	0.002
7.792	0.003	46.740	−0.003	48.748	0.011	49.755	−0.002	49.877	−0.004
7.799	0.005	46.745	−0.002	48.754	0.010	49.760	−0.008	49.883	−0.009
7.807	0.011	46.747	−0.007	48.756	0.008	49.763	−0.014	49.886	−0.010
7.814	0.013	46.752	−0.003	48.765	−0.005	49.768	−0.017	49.892	−0.019
7.822	0.009	46.754	0.009	48.770	−0.010	49.770	−0.018	49.895	−0.008
7.828	0.005	46.759	0.018	48.774	−0.018	49.775	−0.023	49.900	−0.019
7.835	0.010	46.761	0.012	48.781	−0.019	49.778	−0.018	49.903	−0.024
7.840	0.015	46.766	0.016	48.786	−0.018	49.783	−0.021	49.908	−0.017
7.843	−0.003	46.768	0.011	48.789	−0.019	49.786	−0.020	...	...
7.848	0.008	46.773	0.019	48.795	−0.011	49.791	−0.015	...	...

exist because Breger (1972), with only three nights in a time span of three years, also obtains similar results. More recently reported values of the period were published by Rodríguez & Breger (2001) as 0.1400 and 0.1594 d for W2 and W20, respectively. Although the results are not exactly the same as ours and since they do not describe their analysis, we can only assume that there is some significance around 7.18 and 7.43 c/d for W2 and W20, respectively.

If a similar analysis is carried out with our data, but considering only the three consecutive nights to minimize aliasing problems, although accuracy is lost, we get aliases in the third determined frequency for W2 and for the first and third frequencies of W20, making it impossible to determine accurately from the period ratios the modes in which the stars are pulsating.

Reddening, absolute magnitude and distance were determined through the calibrations described by Nissen (1988). In this procedure, the intrinsic color index $(b-y)_0$ was first calculated by the expression for F stars (with $2.59 < \beta < 2.72$):

$$(b-y)_0 = K + 1.11\Delta\beta + 2.7(\Delta\beta)^2 - 0.05\delta c_0 - (0.1 + 3.6\Delta\beta)\Delta\delta m_0 \,, \quad (1)$$

for A stars (with $2.72 < \beta < 2.88$):

TABLE 3

DIFFERENTIAL PHOTOMETRY OF THE DELTA SCUTI STAR W20 IN THE V FILTER

Time	ΔV	Time	ΔV	Time	ΔV	Time	ΔV	Time	ΔV
6.793	−0.005	7.832	0.002	46.770	0.003	48.785	−0.022	49.787	0.003
6.800	−0.017	7.838	0.001	46.772	0.001	48.790	−0.017	49.790	−0.001
6.807	−0.016	7.865	0.003	46.777	−0.003	48.794	−0.017	49.796	0.002
6.814	−0.014	7.873	−0.001	46.779	−0.015	48.799	−0.011	49.799	0.004
6.827	−0.004	7.879	−0.004	46.784	−0.003	48.802	−0.002	49.805	−0.005
6.833	−0.021	7.896	−0.008	46.786	−0.017	48.809	0.000	49.808	−0.012
6.841	−0.011	46.688	0.016	48.695	0.015	48.814	0.006	49.811	−0.012
6.847	0.003	46.694	0.010	48.698	0.017	48.817	0.015	49.815	−0.010
6.854	0.003	46.697	0.010	48.703	0.017	48.822	0.026	49.818	−0.012
6.862	−0.001	46.701	0.017	48.706	0.017	48.823	0.035	49.822	−0.011
6.870	0.011	46.703	0.006	48.711	0.017	49.710	−0.011	49.828	−0.015
6.876	0.030	46.706	0.007	48.714	0.014	49.713	−0.010	49.831	−0.009
6.892	0.045	46.709	0.000	48.719	0.007	49.718	0.001	49.837	−0.003
6.900	0.027	46.714	−0.001	48.821	0.010	49.720	0.009	49.840	−0.001
6.905	0.022	46.717	−0.010	48.727	0.011	49.724	−0.001	49.847	0.001
6.915	0.022	46.722	−0.007	48.729	0.011	49.733	0.006	49.853	−0.001
6.922	0.022	46.723	−0.011	48.734	0.003	49.736	0.017	49.856	−0.003
6.927	0.012	46.728	−0.014	48.737	0.003	49.741	0.009	49.862	−0.004
6.935	0.009	46.730	−0.007	48.742	0.000	49.743	0.001	49.864	−0.003
6.946	−0.001	46.734	−0.010	48.745	0.006	49.749	0.006	49.870	0.002
6.952	−0.008	46.736	−0.007	48.749	−0.011	49.751	0.013	49.873	−0.003
6.960	−0.028	46.741	−0.017	48.752	−0.007	49.756	0.001	49.879	−0.009
6.966	−0.033	46.743	−0.006	48.758	−0.013	49.758	0.011	49.881	−0.003
6.975	−0.028	46.748	−0.004	48.761	−0.010	49.763	0.006	49.887	0.002
7.796	−0.002	46.751	−0.011	48.765	−0.021	49.766	0.009	49.890	0.004
7.804	0.000	46.755	−0.005	48.768	−0.023	49.772	−0.001	49.896	0.003
7.811	0.008	46.758	0.003	48.774	−0.032	49.774	0.002	49.899	0.007
7.819	0.012	46.763	0.007	48.777	−0.029	49.779	0.003	49.904	−0.002
7.825	0.002	46.765	0.002	48.782	−0.024	49.782	−0.001	49.904	−0.002

$$(b-y)_0 = 2.946 - 1.00\beta - 0.1\delta c_0\,, \tag{2}$$

with

$$\Delta\beta = 2.72 - \beta\,, \tag{3}$$
$$\delta m_0 = m_{1,\mathrm{Hyades}(\beta)} - m_0\,, \tag{4}$$
$$\delta c_0 = c_0 - c_{1,\mathrm{std}(\beta)}\,. \tag{5}$$

The absolute magnitude is

$$M_V = M_{V,\mathrm{ZAMS}(\beta)} - f\delta c_0\,, \tag{6}$$

and with: $f = 9+20\beta$ for F type stars and $f = 9$ for A type stars. Once the absolute magnitude and the reddening are determined, the distance is calculated in the customary way.

The metallicity is determined through the relation (Nissen 1988):

$$[\mathrm{Fe/H}] = -[10.5 + 50(\beta - 2.626)]\delta m_0 + 0.12\,. \tag{7}$$

The physical characteristics $\log T_{\rm e}$ and $\log g$ were determined through a semi-empirical approach utilizing computed calibration grids based on synthetic

TABLE 4

STRÖMGREN $uvby\beta$ PHOTOMETRY VALUES OF THE VARIABLE STARS

ID	V	$b-y$	m_1	c_1	β	Source
W2	9.730	0.136	0.187	0.992	2.784	CR
	9.709	0.131	0.173	0.953	2.824	PP
	9.720	0.134	0.180	0.973	2.804	mean
W20	10.270	0.270	0.190	0.740	2.700	SSY
	10.320	0.243	0.225	0.719	2.706	CR
	10.314	0.260	0.191	0.743	2.720	PP
	10.301	0.258	0.202	0.734	2.709	mean
	0.027	0.014	0.020	0.013	0.010	Std. Dev.

TABLE 5

RESULTS OBTAINED AFTER THE ANALYSIS WITH PERIOD

	F_1(c/d)	A_1 (mag)	Phase 1	F_2(c/d)	A_2	Phase 2	F_3(c/d)	A_3	Phase 3
W2	7.1865	0.019	0.058	10.5026	0.006	0.731	4.7174	0.004	0.748
W20	7.4385	0.016	0.029	7.1283	0.011	0.973	12.674	0.005	0.444

TABLE 6

UNREDDENED VALUES OF W2 AND W20 STARS

ID	$E(b-y)$	$(b-y)_0$	c_0	β	m_0	V_0	M_V	DM	Distance (pc)	[Fe/H]
W2	0.010	0.124	0.971	2.804	0.183	9.67	1.08	8.59	523	⋯
W20	0.031	0.227	0.728	2.709	0.211	10.17	1.53	8.64	535	0.670

colors from unreddened color indexes (Relyea & Kurucz 1978).

The reddening and the unreddened parameters for the δ Scuti stars and a summary of the photoelectric photometry of the W2 and W20 stars are presented in Table 6, whereas the derived physical characteristics are presented in Table 7.

In a separate analysis of the absolute photometry of NGC 2264, Peña et al. (2002) consider whether these variable stars actually belong to the cluster. Lang (1992) reports a distance to NGC 2264 of 750 pc with no uncertainities provided. Peña et al. (2000; 2002), adopting the same calibrations described in this paper, from a compilation of the $uvby\beta$ data of the sources previously described, determined mean values and a standard deviation for the member stars of two clusters in the direction of NGC 2264 for $E(b-y)$ (in magnitudes), distance (in parsecs) and metal content. The numerical values for each cluster were 0.025 ± 0.025 mag, 688 ± 103 pc and $\log z/z_0 = -0.38 \pm 0.260$ for NGC 2264a and 0.027 ± 0.057 mag, 300 ± 63 pc and $\log z/z_0 = 0.560 \pm 0.411$, for NGC 2264b, respectively.

We estimate the distances to WV588 Mon and V589 Mon to be somewhere between these values, at 523 and 535 pc, respectively. The uncertainties were merely taken as the standard deviation of the distance of W20, the only star with three independent determinations for which the standard deviation would have any significance at all, however limited. An evaluation of the distance values were calculated for the several values for each index listed in Table 4. This same uncertainty was also considered for W2 which has practically the same dispersion. With these assumptions, the uncertainty in the distance modulus was of 0.287 mag and in distance of 71 pc. Hence all the previous discussion is still valid since it would be difficult, given the scattered values found, to assign the membership of any of them to either of the presumed two clusters in the direction of NGC 2264.

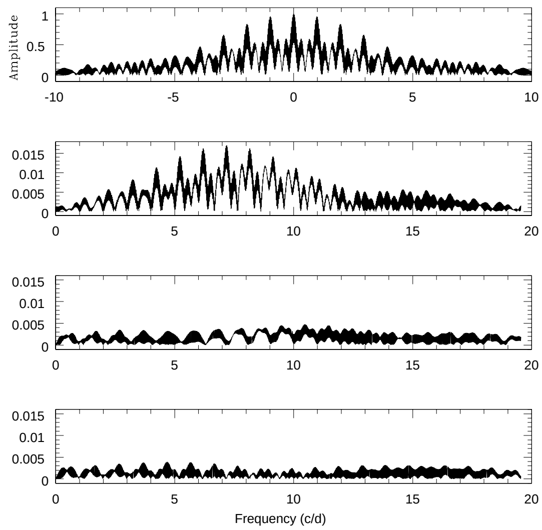

Fig. 3. Periodogram of W2. Top, window function. Going from upper to lower panels, prewhitening of the frequencies presented in Table 4 is carried out until the noise level is reached, bottom.

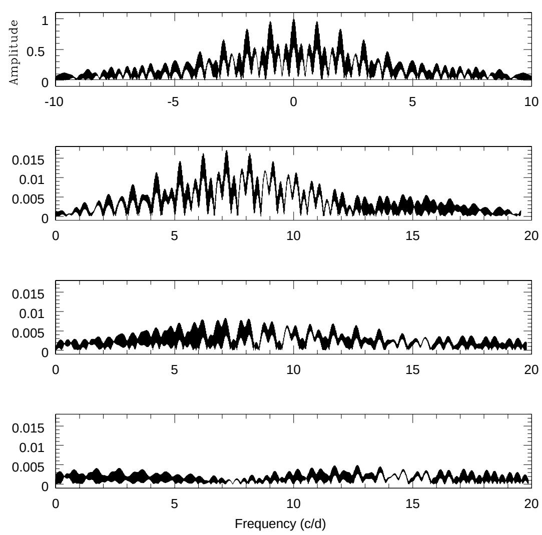

Fig. 4. Periodogram of W20. Panels as in Figure 3.

The Tycho I parallaxes in Hipparcos & Tycho catalogues (1997) for these stars (76 ± 29 mas and 91 ± 48 for V588 Mon and V589 Mon, respectively) suggest they are only 13 ± 5 and 11 ± 6 pc away. We are investigating this problem through a thorough study of the stars in NGC 2264 and other better-studied clusters. Given the wide range of distances derived for the stars and the cluster, we have serious doubts about the certainty of cluster membership. This may help to resolve the paradox of the presence of pre-main-sequence δ Scuti stars in such a young open cluster (Breger 1972; Kurtz 1999; Rodríguez & Breger 2001) like NGC 2264.

TABLE 7

PHYSICAL PARAMETERS OF THE δ SCUTI STARS CONSIDERED

ID	M_V	$M_{\rm bol}$	$\log T_{\rm e}$	$\log g$	Period (d)
W2	1.54	1.35	3.903	3.7	0.1391
W20	1.74	1.5	3.851	3.6	0.1344

4. CONCLUSIONS

A set of frequencies was obtained from differential photometric data which, along with the physical characteristics of these variable stars derived from the Strömgren $uvby\beta$ absolute photometry, has served to parametrize these stars. Large discrepancies between the photometrically derived distances and values from the Tycho Catalogue raise questions about whether either star is a member of NGC 2264. We recommend multi-site, well-coordinated campaigns for each variable star before definitive frequency sets are assigned, in order to correctly describe their pulsational nature. A thorough study of the NGC 2264 cluster through Strömgren $uvby\beta$ photometry is being carried out.

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