Photometric Study of Variable Stars in the Open Cluster NGC 6866

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ABSTRACT

We report the discovery of 19 variable stars and two blue–stragglers in the field of the open cluster NGC 6866. Three of the variable stars we classify as $\delta$ Sct, two, as $\gamma$ Dor, four, as W UMa, two, as ellipsoidal variables, and one, as an eclipsing binary. Seven stars show irregular variability. Two of the pulsators, a $\delta$ Sct star NGC 6866-29 and a $\gamma$ Dor star NGC 6866-21, are multiperiodic.

From an analysis of proper motions, we conclude that the $\delta$ Sct stars, one of the $\gamma$ Dor stars and both blue–stragglers are very probable members of the cluster. The position on the color-magnitude diagram of seven other variables suggests that they also belong to the cluster. The eclipsing binary, which we discover to be a new high-velocity star, and the seven irregular variables are non-members.

Then, we discuss in detail the age and metallicity of open clusters that host $\gamma$ Dor stars and we show that none of these parameters is correlated with the number of $\gamma$ Dor stars in cluster.

Key words: Stars: pulsating: $\delta$ Sct – Stars: pulsating: $\gamma$ Dor – Stars: variable: other – Open clusters: individual: NGC 6866 – Space missions: Kepler

1. Introduction

NGC 6866 ($\alpha_{2000} = 20^h03^m55^s$, $\delta_{2000} = 44^\circ09'30''$) is an intermediate-age open cluster classified as I2p by Trumpler (1928) or II2m by Ruprecht (1966). The cluster falls into the field of view of the Kepler satellite telescope which will observe selected stars from the Cygnus–Lyra region with the aim of searching for Earth-size planets and a detailed study of the structure of pulsating stars by means of the asteroseismic analysis (Christensen-Dalsgaard et al. 2006).

The first photometric study of the cluster dates back to the $UBV$ photoelectric and photographic photometry of Hoag et al. (1961), Johnson et al. (1961), and Barkhatova & Zakharova (1970). Hoag et al. (1961) and Johnson et al. (1961) derived the distance modulus of the cluster, $V - M_V = 10.82$ mag, the color excess, $E(B-V) = 0.14$ mag, the distance, $d = 1200$ pc, and estimated the spectral type of the turn-off point to be A3. Subsequent observations of Sutanto & Hidajat (1972) yielded $E(B-V) = 0.16$ mag and $V - M_V = 11.10$ mag. The catalogue
of astrophysical data for Galactic open clusters of Kharchenko \textit{et al.} (2005) gives $E(B-V) = 0.17$ mag, $d = 1450$ pc, and $V - M_V = 11.33$ mag.

The estimates of the age of NGC 6866 range from 0.23 Gyr (Lindoff 1968) to 0.65 Gyr (Loktin \textit{et al.} 1994) with the most recent determination, 0.48 Gyr, given by Kharchenko \textit{et al.} (2005). The mean [Fe/H] of the cluster has been derived by Loktin \textit{et al.} (1994) from the photometry of Hoag \textit{et al.} (1961) to be equal to $+0.10$ dex. The mean radial-velocity of the cluster has been measured by Mermilliod \textit{et al.} (2008) and by Frinchaboy \textit{et al.} (2008); these authors found the radial-velocity to be equal to $13.68 \pm 0.06$ and $12.18 \pm 0.75$ km/s, respectively. (Here, the uncertainty given by Mermilliod \textit{et al.} (2008) is an r.m.s. error, while the uncertainty given by Frinchaboy \textit{et al.} (2008), the standard deviation.)

The probability of the cluster membership has been computed by Baumgardt \textit{et al.} (2000) for two stars, by Dias \textit{et al.} (2002), for 89 stars, by Kharchenko \textit{et al.} (2004), for 192 stars, and by Frinchaboy \textit{et al.} (2008), for 52 stars (all in common with Dias \textit{et al.} (2002)). Baumgardt \textit{et al.} (2000) and Dias \textit{et al.} (2002) based their computations on proper motions from the Tycho-2 catalogue (Högn \textit{et al.} 2000). Kharchenko \textit{et al.} (2004) used proper motions from the Tycho-2 catalogue, the available photometry and the stars’ positions in the cluster. Frinchaboy \textit{et al.} (2008) used radial velocities measured with the Hydra multi-object spectrographs, proper motions from the Tycho-2 catalogue, and the angular distance of the stars from cluster center. All these papers concern stars brighter than $V = 13$ mag and altogether list 48 stars for which the membership probability, $P$, is higher than 60%.

We note, however, that Frinchaboy \textit{et al.} (2008) perform separate computations of cluster membership from proper motions, $P_{\text{pm}}$, and from radial velocities, $P_{\text{rv}}$. Since for many stars these values differ significantly from each other, and because the final value of $P$ computed by Frinchaboy \textit{et al.} (2008) is a product of $P_{\text{pm}}$ and $P_{\text{rv}}$, these authors find only one star for which $P > 90\%$, two, for which $P \approx 50\%$, one, for which $P \approx 20\%$, ten, for which $P \leq 10\%$, and 38, for which $P = 0$. These differences between $P_{\text{pm}}$ and $P_{\text{rv}}$ computed by Frinchaboy \textit{et al.} (2008), differences between $P_{\text{pm}}$ derived by Frinchaboy \textit{et al.} (2008) and by Dias \textit{et al.} (2002) from the same data (where $P_{\text{pm}}$ given by Frinchaboy \textit{et al.} (2008) is always lower than $P_{\text{pm}}$ computed Dias \textit{et al.} (2002)), and the very low number of stars classified by Frinchaboy \textit{et al.} (2008) as cluster members is very unexpected. Because the origin of these discrepancies is not clear and their study is beyond the scope of this paper, in the following Sections we will take with care the probabilities computed by Frinchaboy \textit{et al.} (2008) and refer only to the results obtained by Dias \textit{et al.} (2002) and Kharchenko \textit{et al.} (2004).

So far, the cluster has not been a subject of a variability search. The Hipparcos Catalogue (ESA 1997) classifies two stars, HIP 98610 and 98793, as unsolved variables ($U$), and the Tycho Catalogue (ESA 1997), five, HD 190044, 190465, 190657, 190966, and TYC2-3162-00893-1, as suspected variables ($W$).
The paper is organized as follows. In Sect. 2, we give an account of the observations and reductions. In Sect. 3, we compute the cluster membership of stars in the field of NGC 6866 and discuss the new variables. In Sect. 4, we construct the color-magnitude diagram for NGC 6866 and discover two blue-stragglers, the first such objects in the cluster. In Sect. 5 we discuss the issue of the age and metallicity of the open clusters in which γ Dor stars can exist. Sect. 6 contains a summary.

The numbering system of stars in NGC 6866 used in this paper is adopted from the WEBDA [database].
2. Observations and Reductions

Our observations were carried out at the Białków Observatory of the Wrocław University on 14 nights between April 27 and July 21, 2007. We used a 60-cm Cassegrain telescope equipped with Andor DW432-BV back-illuminated CCD camera to observe one $12.8 \times 11.7$ arcmin$^2$ field in NGC 6866. We used $B$ and $I_C$ filters of the Johnson-Kron-Cousins $UBV(RI)_C$ photometric system and collected 413 CCD frames in the $B$ filter, 470, in $V$, and 469, in $I_C$. The exposure times were equal to 60 – 100 s, depending on the filter and the weather conditions.

In the pre-processing of the frames, the bias and dark frames were subtracted, the flat-field correction was applied, and the frames in the $I_C$ filter were corrected for the fringing pattern. For all stars in the field the instrumental magnitudes were computed using the DAOPHOT profile-fitting software (Stetson 1987). The reductions were done as described by Jerzykiewicz et al. (1996).

In the $I_C$-band reference frame of the field, we identified 3798 stars for which we obtained meaningful photometry. The finding chart for the field we observed is shown in Fig. 1. To avoid crowding, we show only stars brighter than 18 mag in $V$.

We derived the differential photometry on a frame-to-frame basis, so that the instrumental photometry for each frame had to be shifted to a common magnitude scale defined by a selected reference frame as described by Kopacki et al. (2008). Then, the average $v$ instrumental magnitudes and the $(b - v)$ colors-indices of all
Table 1
Mean differences between the $V$ magnitudes and $(B - V)$ colors from this paper and from the literature.

|                     | $\Delta V$ [mag] | $\Delta (B - V)$ [mag] |
|---------------------|------------------|------------------------|
|                     | mean  | $\sigma$ | N | $N_{\text{rej}}$ | mean  | $\sigma$ | N | $N_{\text{rej}}$ |
| photoelectric:      |       |          |   |                 |       |          |   |                 |
| Hoag et al. (1961)  | 0.002  | 0.023    | 24 | 0               | -0.011 | 0.054    | 24 | 0               |
| photographic:       |       |          |   |                 |       |          |   |                 |
| Hoag et al. (1961)  | 0.018  | 0.065    | 81 | 3               | 0.015  | 0.065    | 84 | 0               |
| Barkhatova and Zakharova (1970) | 0.006  | 0.094    | 150 | 5               | -0.001 | 0.148    | 147 | 8               |
| Hidajat and Sutantyo (1972) | 0.037  | 0.128    | 134 | 17              | 0.059  | 0.146    | 145 | 6               |

stars were transformed to the standard system using following equations

\[
V - v = -0.107 (b - v) - 1.232, \quad \sigma = 0.019 \text{ mag},
\]
\[
B - V = +1.276 (b - v) - 0.160, \quad \sigma = 0.016 \text{ mag},
\]

that were obtained by the method of least squares from 24 bright stars in common with Hoag et al. (1961). Here, $\sigma$ denotes standard deviation of the fit, $V$, the standard magnitude, and $(B - V)$, the standard color index.

In Fig. 2, we plot the differences between the $V$ magnitudes and $(B - V)$ colors from this paper and those from Hoag et al. (1961), Barkhatova & Zakharova (1970), and Hidajat & Sutantyo (1972). In Table 1, we give the mean values of these differences which we calculated using a $3\sigma$-clipping algorithm for rejecting outlying data points, the standard deviations of the sample, $\sigma$, the number of points used in calculations, $N$, and the number of the rejected data points, $N_{\text{rej}}$. The agreement between our measurements and those given in the literature is reasonably good. The $V$ magnitudes and $(B - V)$ colors from this paper are given in Table 3, available in electronic form from the Acta Astronomica Archive.
Table 2
Photometric data for variable stars in NGC 6866

| Var No | Type   | α2000  | δ2000  | V  | B − V | ΔB  | ΔV  | ΔiC | P  |
|--------|--------|--------|--------|----|-------|-----|-----|-----|----|
|        |        | [h m s] | [° ′ ″] |    | [mag] | [mag] | [mag] | [mag] | [d] |
| V1     | δ Sct  | 20 04 11.19 | 44 05 33.5 | 12.976 | 0.319 | 0.009 | 0.008 | 0.008 | 0.066677 |
| V2     | δ Sct  | 20 04 03.96 | 44 10 20.7 | 12.376 | 0.302 | 0.006 | 0.006 | 0.007 | 0.072465 |
| V3     | δ Sct  | 20 03 47.13 | 44 09 25.9 | 12.222 | 0.302 | 0.018 | 0.015 | 0.012 | 0.106414 |
|         |        |         |        |     |       |       |       | 0.009 | 0.011 |
|         |        |         |        |     |       |       |       | 0.008 | 0.120744 |
|         |        |         |        |     |       |       |       | 0.004 | 0.006 |
|         |        |         |        |     |       |       |       | 0.003 | 0.085202 |
| V4     | W UMa  | 20 04 26.66 | 44 05 36.2 | –   | –     | –    | –    | –    | 0.601 |
| V5     | W UMa  | 20 03 34.93 | 44 14 50.4 | 13.524 | 0.443 | 0.030 | 0.047 | 0.055 | 0.321742 |
| V6     | – W UMa | 20 04 00.17 | 44 14 03.5 | 17.331 | 0.886 | 0.477 | 0.467 | 0.390 | 0.366528 |
| V7     | – W UMa | 20 03 49.82 | 44 11 08.8 | 17.196 | 0.862 | 0.384 | 0.341 | 0.308 | 0.41501  |
| V8     | Ell    | 20 03 55.96 | 44 10 46.5 | 13.868 | 0.430 | 0.047 | 0.029 | 0.024 | 0.6222 |
| V9     | Ell    | 20 03 38.79 | 44 04 53.1 | 15.543 | 0.773 | 0.213 | 0.193 | 0.169 | 0.43414 |
| V10    | – EA   | 20 04 05.01 | 44 13 56.1 | 13.628 | 0.606 | 0.123 | 0.092 | 0.093 | 1.916 |
| V11    | γ Dor  | 20 03 59.34 | 44 10 26.0 | 13.919 | 0.431 | 0.100 | 0.069 | 0.043 | 0.8057 |
| V12    | γ Dor  | 20 03 54.18 | 44 06 46.2 | 12.644 | 0.228 | 0.020 | 0.016 | 0.013 | 0.7077 |
| V13    | 20 Irr | 20 03 27.92 | 44 09 19.4 | 13.571 | 0.431 | 0.146 | 0.121 | 0.079 | – |
| V14    | 20 Irr | 20 04 20.84 | 44 10 04.2 | 15.796 | 1.180 | 0.279 | 0.176 | 0.113 | – |
| V15    | 3110 Irr | 20 04 08.29 | 44 07 51.2 | 13.080 | 2.043 | 0.133 | 0.097 | 0.047 | – |
| V16    | 1220 Irr | 20 03 26.72 | 44 10 49.3 | 13.751 | 2.120 | 0.223 | 0.083 | 0.035 | – |
| V17    | 150 Irr | 20 04 30.15 | 44 06 14.8 | 14.514 | 2.049 | 0.284 | 0.218 | 0.076 | – |
| V18    | Irr    | 20 04 19.00 | 44 07 06.0 | 15.570 | 2.108 | 0.770 | 0.395 | 0.148 | – |
| V19    | Irr    | 20 04 27.38 | 44 11 01.4 | 16.231 | 2.209 | 1.048 | 0.569 | 0.289 | – |

3. Variable Stars

For each star, the Fourier spectrum and an AoV periodogram (Schwarzenberg-Czerny 1989) were computed in the frequency range from 0 to 50 d$^{-1}$. These two methods were used because the former is useful for stars of which the brightness varies sinusoidally, while the latter, for eclipsing binaries. Then, we calculated the signal-to-noise ratio, $S/N$, of the highest peak in each spectrum and checked by eye the phase-diagrams corresponding to stars with $S/N \geq 4$ for the presence of a periodic variability or eclipses. In Fig. 3, we plot the $S/N$ ratio of the highest peak in the frequency spectrum (in the figure we show only the 0–20 d$^{-1}$ part of the spectrum) against its frequency for all stars in the field.

We discovered 19 variable stars which we classified on the basis of the length of the detected period and the shape of the light-curve. We designated these stars V1 through V19. The stars are listed in Table 2, where we give their designation, the number from WEBDA, type of variability, equatorial coordinates, the mean brightness in $V$ and the mean color-index $(B − V)$ for all stars but the faintest V4 for which we do not compute the standard magnitudes, the range of variability in
Fig. 3. The signal-to-noise ratio (S/N) of the highest peak in the frequency spectrum of the I-filter data for each star in the field we observed. Variable stars are indicated with the following symbols: δ Sc, triangles, γ Dor, asterisks, W UMa, diamonds, the EA system, a square, ellipsoidal variables, bullets, and irregular variables, encircled plus signs.

B, V and the instrumental $i_C$ filter, and for the periodic variables, the period(s), $P$.

The variability of HIP 98793, NGC 6866-5, classified in the Hipparcos Catalogue as an unsolved variable, has not been confirmed in our data. We also do not confirm variability of this star in Hipparcos $H_p$ magnitudes. The remaining suspected and unsolved variables listed in the Hipparcos and the Tycho Catalogues were not included in our field of view.

3.1. Cluster Membership

Only two of the 19 variables discovered in this paper have the cluster membership probability computed by Dias et al. (2002) or Kharchenko et al. (2004). Therefore, we used the proper motions from Röser et al. (2008) to compute the probability of membership in the cluster for stars from our field. First, we used stars that fall into the cluster area centered at $\alpha_{2000}=20^{h}.065$, $\delta_{2000}=44^{\circ}.16$ and limited by the radius of $0^{\circ}.14$ adopted from Kharchenko et al. (2005) to compute the mean proper motion of the cluster. The computations were done iteratively; we used a $\sigma$-clipping algorithm and rejected stars having the proper motion that differed from the mean proper motion by more than $3\sigma$. The resulting value, $\mu_\alpha \cos \delta = -3.86 \pm 0.16$, $\mu_\delta = -4.63 \pm 0.17$ mas/yr (the uncertainty given here is the r.m.s. error), agrees well with the mean cluster proper motion computed by Dias.
Fig. 4. Fourier spectra of the δ Sct star V1: (a) for original V-filter observations, (b) after prewhitening with frequency $f_1 = 14.9976$ d$^{-1}$ (the ordinate scale is the same in both panels); (c) the light curves of V1 in B (triangles), V (squares) and the instrumental $i_C$ filter (circles). $\Delta B$ and $\Delta i_C$ are magnitude shifts applied to B and $i_C$ data, respectively.

Fig. 5. The same as in Fig. 4 but for the δ Sct star V2. (a) The highest peak occurs at the frequency $f_1 = 13.7999$ d$^{-1}$ (the ordinate scale is the same in both panels). (c) The light curves of V2 in B (triangles), V (squares) and the instrumental $i_C$ filter (circles). $\Delta B$ and $\Delta i_C$ are magnitude shifts applied to B and $i_C$ data, respectively.

et al. (2002), $\mu_\alpha \cos \delta = -3.33 \pm 2.93$, $\mu_\delta = -5.03 \pm 2.93$ mas/yr, and Kharchenko et al. (2005), $\mu_\alpha \cos \delta = -3.48 \pm 0.40$, $\mu_\delta = -5.80 \pm 0.38$ mas/yr. The agreement with the values given by Frinchaboy et al. (2008), $\mu_\alpha \cos \delta = -5.5 \pm 1.2$, $\mu_\delta = -8.0 \pm 1.1$, is less satisfactory. We note that the uncertainties given by Dias et al. (2002) and Frinchaboy et al. (2008) are standard deviations while Kharchenko et al. (2005) give the r.m.s. errors.

Then, following Kharchenko et al. (2005), for each star for which the proper motion has been measured, we computed the cluster membership probability, $P$, as a measure of its deviation from the mean proper motion of the cluster, $d$. In the result, 23 stars with $d \leq \sigma$ (where $\sigma$ is the standard deviation of the proper motions of the sample), i.e., $P > 60\%$, we classified as most probable cluster members, 20 stars with $1\sigma \leq d < 2\sigma$, i.e., $14\% \leq P \leq 60\%$, as possible members, 11 stars with $2\sigma \leq d < 3\sigma$, i.e., $1\% \leq P \leq 14\%$, as possible field stars, and 19 stars with $d < 3\sigma$,
Fig. 6. Similar as in Fig. 4 but for the δ Sct star V3. The highest peaks occur at (a) $f_1 = 9.3973$ d$^{-1}$, (b) $f_2 = 8.2820$ d$^{-1}$ and (c) $f_3 = 11.7368$ d$^{-1}$ (the ordinate scale is the same in all panels.)

(e) The light curves of V3 in B (triangles), V (squares) and the instrumental iC filter (circles), prewhitened with the frequencies $f_2$ and $f_3$, and phased with the frequency $f_1$: (f) – (g) the same as in (e) but for the frequencies $f_2$ and $f_3$. $\Delta B$ and $\Delta i_C$ are magnitude shifts applied to B and iC data, respectively.

i.e., $P < 1\%$, as definite field stars. The cluster membership probability computed in this paper is listed in the last column of Table 3.

Our computations show that the δ Sct stars V1, V2 and V3, and the γ Dor star V12 belong to the cluster. The eclipsing binary, V10, and one of the irregular variables, V13, are definite field stars. For the other irregular variable V15, the cluster membership probability is 30% so that it could be a cluster member. However, its location on the color-magnitude diagram far to the red of the main sequence (see Fig. 11) rules out that possibility.

3.2. δ Sct stars

We discovered two monoperiodic δ Sct stars, V1 and V2, and one multi-periodic δ Sct star, V3. V1 and V2 vary with the frequencies $f_1 = 14.9976$ and $f_1 = 13.7999$ d$^{-1}$, respectively. V3 shows three frequencies, $f_1 = 9.3973$, $f_2 = 8.2820$ and $f_3 = 11.7368$ d$^{-1}$. All these stars lie on the main sequence in the cluster’s color-magnitude diagram (see Fig. 11) and for all the probability of cluster membership is high: 80%, 71% and 87% for V3 computed by, respectively, Dias et al. (2002), Kharchenko et al. (2004) and in this paper, and 72% and 94% computed for V1 and V2 in this paper. Therefore, we consider all these stars to be
very probable members of NGC 6866.

We show the amplitude spectra of V1 and V2 in Figs. 4 and 5, respectively, and that of V3, in Fig. 6. The amplitude spectra of the residuals, plotted in Figs. 4b, 5b and 6d show only noise. In Figs. 4c, 5c and Fig. 6e-g, we plot the phase diagrams constructed from $B$, $V$ and the instrumental $i_C$ magnitudes. As can be seen from these figures, the stars show sinusoidal variations of the brightness in all filters.

3.3. W UMa and Ell stars

We discovered four W UMa type variables, V4, V5, V6 and V7, and two ellipsoidal variables, V8 and V9. We show their light curves in Fig. 7. For V4, we show only $i_C$– filter light curve because in the other filters the scatter masks the variation.

3.4. The eclipsing binary

Our time-series of V10 shows two minima which have the same shape of the ingress (the egress was observed only partially) and which we interpret as the same type of minimum. The $BVic$ light-curves, phased with $P_{\text{orb}} = 1.916$ d, are plotted in Fig. 8; we have checked that neither $0.5P_{\text{orb}}$ nor any other period fits the data. The observed minimum is flat. The brightness between eclipses is not constant.
The proper motion of V10, $\mu_\alpha \cos \delta = -37.75 \pm 14.13$, $\mu_\delta = -54.14 \pm 14.3$ mas/yr (Röser et al. 2008), is around ten times higher than the mean proper motion of the cluster. The cluster membership probability of V10 computed in this paper is lower than 1%. Having reached the conclusion that V10 is a definite field star and keeping in mind its high proper motion, we suspected that V10 is a high-velocity metal-deficient Population II star.

Because our data do not allow deciding whether the primary or the secondary minimum has been observed, we calculated the range of magnitudes of the primary and the secondary component of V10 which give the observed magnitude at the quadrature, $V = 13.33$, $B = 13.76$ mag, and at the minimum, $V = 13.41$, $B = 13.86$ mag. Because the orbital inclination of the system has not been measured, in our calculations we adopted $i = 90^\circ$. The calculated magnitudes cover all the possible combinations of the magnitudes of the components, i.e., from the secondary component being so faint that it does not contribute to the mean brightness of the system outside eclipses to both components having the same brightness. The resulting $B$ and $V$ magnitudes of the primary, 1, and the secondary, 2, components fall into the following ranges: $m_{V,1} \in (13.33; 14.09)$, which corresponds to $m_{V,2} \in (+\infty; 14.09)$, and $m_{B,1} \in (13.76; 14.52)$, which corresponds to $m_{B,2} \in (+\infty; 14.52)$ mag.

Since we aimed at calculating the lower limit of the tangential velocity of V10, we assumed that the star is a not reddened metal-deficient dwarf, and that the brightness of its primary component is $V = 13.33$; any change in our assumptions, e.g., an increase of $E(B-V)$, higher magnitude of the primary component, or a higher metallicity (i.e., brighter absolute magnitude), would result in a higher tangential velocity of the star. We calculated the star’s absolute magnitude, $M_V = 4.9$, from
3.5. \( \gamma \) Dor stars

Two stars in NGC 6866 show variability on time-scale of a day: V11, which shows two frequencies, \( f_1 = 1.2412 \text{ d}^{-1} \) and \( f_2 = 1.1038 \text{ d}^{-1} \), and V12, which shows one frequency, \( f_1 = 1.4130 \text{ d}^{-1} \). For both stars, the amplitudes are the highest in the B filter and the smallest, in \( i_C \), and the light-curves are sinusoidal. The amplitude spectra and phase diagrams for V11 and V12 are shown in Figs. 9 and 10.

\( M_V - (B-V) \) relation of Karataş & Schuster (2006) for metal-poor stars. Then, we calculated the distance to the star, \( r = 489 \text{ pc} \), and its tangential velocity, 152 km/s. Since the calculated value is higher than 100 km/s, which is the lower limit of tangential velocity of high-velocity stars (see, e.g., Lee (1984)), we classify V10 as a new high-velocity star in the field of NGC 6866.
Fig. 11. (a) The standard \((B - V)\) vs. \(V\) and (b) the instrumental \((v - i_C)\) vs. \(V\) color–magnitude diagrams for NGC 6866. δ Sct stars are indicated with triangles, γ Dor, with asterisks, W UMa, with diamonds, the eclipsing binary, with a square, ellipsoidal variables, with bullets, and irregular variables, with encircled plus signs. Panel (b) does not include V19 for which \((v - i_C) = 4.48\) mag.

Fig. 12. A zoom of Fig. 11a. Circles indicate stars for which the membership probability is higher than 60%. Blue–stragglers are indicated with open diamonds, red giants, with crosses. δ Sct stars are indicated with triangles, γ Dor stars, with bullets; the remaining variables are not included. The intersection of the dashed lines indicates the turn-off point of the cluster, i.e., \(m_v\) and \((B - V)\) of an A3V star in a distance of 1200 pc and reddened with \(E(B - V) = 0.14\) mag. NGC 6866–7 is a rejected blue–straggler candidate.
The probability of membership of V12 in NGC 6866 is 97% or 66% according to Kharchenko et al. (2004) and this paper, respectively. The cluster membership of V11 has not been computed. However, as both stars fall on the cluster main sequence, we consider both V11 and V12 to be probable cluster members.

Having discovered the multiperiodic variability of V11, and taking into account the length of the detected periods, we classify the star as a $\gamma$ Dor – type variable. The other star, V12, we classify as a $\gamma$ Dor suspect on the basis of the length of the detected period and the increase of the amplitude of its variability towards the shorter wavelengths.

In Sect. 5, we discuss the phenomenon of the occurrence of $\gamma$ Dor stars in open clusters in more detail.

3.6. Irregular variables

The irregular variables V13, V14, V15, V16, V17, V18 and V19 form the largest group of variable stars discovered in the field of NGC 6866. We computed the probability of membership in the cluster for V13 and V15. V13, which falls on the cluster main sequence (see Fig. 11), turned out to be a definite field star, and V15, which might be a probable cluster member, is excluded as such because of its position far to the red of the cluster main sequence. Therefore, we consider all the irregular variables to be non-members.

4. The Color – Magnitude Diagram

In Fig. 11a and b, we show $V$ vs. $(B-V)$ and $V$ vs. the instrumental $(v-i_c)$ color-magnitude diagrams for stars in the field of NGC 6866 for which we have reliable photometry. The intersection of the dashed lines in Fig. 12b indicates the turn-off point of the cluster, A3, estimated by Johnson et al. (1961).

As can be seen from these figures, most stars fall on the main sequence; the red giant clump is not visible. Indeed, in NGC 6866 there are only four red giants listed by Mermilliod et al. 2008: NGC 6866-1, 5, 26 and 31. (We note, however, that NGC 6866-1 has been classified by Sowell (1987) to G5V.) We observed three of these stars; NGC 6866-26 was outside of our field of view.

4.1. Blue–stragglers

NGC 6866 is at the age at which, according to De Marchi et al. (2006), it should host one or two blue–stragglers (see Table 1 in De Marchi et al. 2006). Unfortunately, the only blue–straggler suspect, NGC 6866-7 (Hoag et al. 1961), has been rejected by Ahumada & Lapasset (2007). In the color-magnitude diagram in Fig. 12, this star falls to the red of the main sequence and below the turn-off point and therefore we also reject the possibility that NGC 6866-7 is a blue–straggler.

In Fig. 12, there are, however, two other stars, NGC 6866-1214 and TYC-2 3162-00108-2 (which is the north–east faint component of NGC 6866-5155), that
The list of Galactic open clusters which host candidates for γ Dor stars.

| Cluster      | \( N_{\gamma \text{Dor}} \) | Log Age | \([\text{Fe/H}] \) | Cluster      | \( N_{\gamma \text{Dor}} \) | Log Age | \([\text{Fe/H}] \) |
|--------------|------------------------------|---------|-----------------|--------------|------------------------------|---------|-----------------|
| NGC 581      | 2 [1]                        | 7.1 [2] | −0.85 [3]       | NGC 6633     | 2 [61]                       | 8.6 [25]| −0.30 [22]      |
|              | (1 nm)                       | 7.3 [2] |                 |              |                              | 8.8 [38]| +0.06 [39]       |
| NGC 659      | 3 [4]                        | 7.3 [5] | −0.29 [9]       | NGC 6705     | 2 [40,41]                    | 8.3 [12]| +0.07 [9]        |
|              | (1 nm)                       | 7.6 [6] |                 |              |                              | 8.4 [42]| +0.21 [43]       |
| NGC 1039     | 2 [7]                        | 8.3 [8] | +0.07 [10]      | NGC 6755     | 4 [44]                       | 7.7 [12]| −0.03 [3]        |
|              | (2 nm)                       | 8.4 [8] |                 |              |                              | 8.2 [3] | +0.14 [13]       |
| NGC 1245     | 4 [11]                       | 8.7 [12]| −0.05 [14]      | NGC 6866     | 2 [45]                       | 8.4 [46]| +0.10 [47]       |
|              |                              | 9.0 [13]| +0.10 [15]      |              |                              | 8.8 [47]|                 |
| NGC 1817     | 1 [16]                       | 8.9 [17]| −0.42 [19]      | NGC 7086     | 1 [48]                       | 8.0 [48]|                 |
|              | (1 nm?)                      | 9.1 [18]| +0.18 [15]      |              |                              | 8.1 [12]|                 |
| NGC 2099     | 2 [20]                       | 8.2 [21]| −0.07 [22]      | NGC 7762     | 2 [49,50]                    | 8.4 [12]|                 |
|              | (1 nm?)                      | 8.3 [21]| +0.18 [23]      |              |                              | 9.4 [49]|                 |
| NGC 2301     | 2 [24]                       | 8.2 [25]| +0.01 [23]      | Pleiades      | 2 [37]                       | 7.9 [31]| −0.03 [34]       |
|              |                              | 8.5 [24]| +0.06 [25]      |              |                              | 8.1 [42]| +0.11 [12]       |
| NGC 2506     | 15 [26]                      | 9.1 [12]| −0.57 [28]      | α Per         | 2 [52]                       | 7.7 [53]| −0.05 [51]       |
|              | (1 nm)                       | 9.3 [27]| −0.20 [29]      |              |                              | 8.0 [54]| +0.07 [9]        |
| NGC 2516     | 8 [30]                       | 8.1 [31]| −0.42 [15]      | Coma Ber      | 1 [55]                       | 8.5 [56]| −0.05 [56]       |
|              |                              | 8.2 [32]| +0.02 [15]      |              |                              | 8.7 [38]| −0.03 [58]       |
| NGC 2539     | 1 [31]                       | 8.8 [33]| −0.20 [33]      | Praesepe      | 1 [52]                       | 8.8 [59]| +0.08 [22]       |
|              | (1 nm)                       | 8.9 [33]| +0.16 [16]      |              |                              | 8.9 [52]| +0.27 [60]       |
| NGC 6231     | 3 [34]                       | 6.5 [35]| −0.13 [36]      |              |                              | 6.7 [35]| +0.26 [31]       |

- [1] Wyzykowski et al. 2002, [2] Sanner et al. 1999, [3] Tadross 2003, [4] Pietrzyński et al. 2001, [5] Phelps and Jones 1994, [6] Lata et al. 2002, [7] Kristiansen and Crowe 1996, [8] Jones and Prosser 1996, [9] Cameron 1985, [10] Schuler et al. 2003, [11] Pepper and Burke 2006, [12] WEBDA, [13] Subramaniam 2003, [14] Burke et al. 2003, [15] Gratton 2000, [16] Arentoft et al. 2005, [17] Harris and Harris 1977, [18] Bulagan-Nichita et al. 2004, [19] Frédi and Jones 1993, [20] Hartman et al. 2008, [21] Kallrav et al. 2001, [22] Jones 1979, [23] Pietrini et al. 1995, [24] Kim et al. 2001b, [25] Chen et al. 2003, [26] Arentoft et al. 2007, [27] Kim et al. 2003, [28] Friel and Jones 1993, [29] Carretta et al. 2004, [30] Zerbi et al. 1998, [31] Choo et al. 2003, [32] Bonatto and Bica 2005, [33] Clariá and Lapasset 1996, [34] Arentoft et al. 2001, [35] Baume et al. 1999, [36] Kallrav et al. 1994, [37] Martín and Rodríguez 2002a, [38] Lyon1987, [39] Santos et al. 2009, [40] Koo et al. 2007, [41] Hargis et al. 2005, [42] Magrini et al. 2009, [43] Thogersen et al. 1993, [44] Ciechanowksa et al. 2007, [45] this paper, [46] Lindoff 1968, [47] Loktin et al. 1994, [48] Rosvick and Robb 2006, [49] Maciejewski et al. 2008, [50] Szabo 1999, [51] Boegaard and Fred 1990, [52] Martín and Rodríguez 2002b, [53] Makarov 2006, [54] Stauffer et al. 1999, [55] Martín 2003, [56] Sandage 1958, [57] Friel and Boegaard 1992, [58] Cayrel et al. 1988, [59] Bouvier et al. 2001, [60] Pace et al. 2008, [61] Martín and Rodríguez 2003.

fulfill all the requirements of bona fide blue–stragglers specified by Ahumada & Lapasset (2007): their cluster membership probability is high: 79%, 52% or 90% for NGC 6866-1214, and 74%, 62% or 54% for TYC-23162-00108-2, as computed by Dias et al. (2002), Kharchenko et al. (2004) and in this paper, respectively, (although Frinchaboy et al. (2008) give \( P = 0 \% \) for both stars), both fall into the area of the color-magnitude diagram where blue–stragglers are expected (cf. Fig. 12 of this paper and Figs. 1 and 2 of Ahumada & Lapasset 2007), both are fainter than 2.5 mag limit above the cluster turnoff point, and fall close to the center of the cluster.
Therefore, we classify NGC 6866-1214 and TYC-2 3162-00108-2 as the first blue–stragglers discovered in the field of NGC 6866.

5. Discussion

Hosting one γ Dor star and one γ Dor candidate, NGC 6866 joins the group of 20 galactic open clusters in which a total of 62 candidates for γ Dor type pulsators have been discovered. We list these clusters in Table 4, where we give the number of γ Dor candidates in the cluster (including the non-member γ Dor stars, nm, the number of which, if known, is given below in brackets), and the range of the determinations of the age and metallicity of the cluster. The numbers in square brackets refer to the papers listed at the bottom of the Table. In Fig. 13, we use the shades of gray to plot the number of γ Dor candidates in the log(age) – [Fe/H] plane. Below we discuss the properties of clusters that host γ Dor candidates.

First, we see that, as already noticed by Eyer et al. (2002), there is no relationship between the age of an open cluster and the incidence of γ Dor stars. The phenomenon of γ Dor pulsators can occur in clusters as young as NGC 6231 (3 Myr, Baume et al. 1999) and as old as NGC 2506 (1.8 Gyr, Kim et al. 2001a). An upper limit of the age of γ Dor – hosting open clusters, equal to 250 Myr according to Krisciunas & Patten (1999), does not exist, because around 40 % of the clusters is older than that.

Second, γ Dor stars seem to have little preference concerning the metallicity
of the cluster; [Fe/H] of all but one cluster from Table 4 falls into the range from $-0.2$ to $+0.2$ dex to within its error bars. Moreover, candidates for $\gamma$ Dor stars occur in clusters as metal-rich as Praesepe, [Fe/H] = $+0.27$, and as metal-poor as NGC 581, [Fe/H] = $-0.85$. We note also that although NGC 2506 and NGC 2516, i.e., the clusters in which the number of $\gamma$ Dor candidates is the highest, are the most metal-deficient ones, it needs to be confirmed how many of their $\gamma$ Dor candidates really pulsate and how many are cluster members.

The membership of $\gamma$ Dor candidates in a cluster is another issue that has not been studied sufficiently. For eight clusters only, NGC 581, 1817, 2301, 2516, 6633, 6705, 6866, and 7086, the probability of cluster membership has been derived from the proper motions. For four clusters, NGC 1817, 2516, 6705, and 6866, both proper motions and color-magnitude diagrams were used, leading to different results for some stars (see Arentoft et al. 2005). For NGC 659, 2099, 2506, 2539, 6231, 6755, 7762, and the Pleiades, the cluster membership was determined only from the color-magnitude diagrams, for NGC 1245, from the background star counts (Burke et al. 2004), and for NGC 1039, $\alpha$ Per, Praesepe, and Coma Ber, the probability of membership has not been computed.

The last but not least issue is the mechanism of the observed variability of these stars. All the 22 monoperiodic $\gamma$ Dor candidates detected in the open clusters need to be confirmed as pulsators while the multiperiodic ones require further study to check which of the detected frequencies are due to pulsations and which to, e.g., Ell or $\alpha^2$ CVn type of variability.

Summarizing, we conclude that at the present stage it is not possible to find statistically significant relation between the age or metallicity of an open cluster and the number of $\gamma$ Dor stars therein.

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