Photometric study and detection of variable stars in the open clusters – I. NGC 6866

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1 INTRODUCTION

The study of Galactic open clusters is important for understanding the history of star formation and the nature of the parent star clusters. These systems are used to test stellar models and are vital for our understanding of stellar evolution. By comparing the colour–magnitude diagram (CMD) of a star cluster with theoretical evolutionary models, its age may be estimated and information on the evolution of stars of nearly the same age and chemical composition could be obtained. However, uncertainties in various parameters such as reddening, distance and chemical composition compromise our efforts to measure the age and other parameters. Some cluster members also show various kinds of variability at different stages of their evolution. For example, a wide variety of pulsating variable (PV) stars such as δ Scuti and β Cephei stars are found in open star clusters. Observations of these variables can be used to infer many important stellar parameters such as their mass, radius and luminosity. These parameters are required for an investigation of the relations between rotation, stellar activity, age and mass (Messina et al. 2008, 2010), and imposing constraints on stellar pulsation models. Recent work on cluster variable stars can be found in Hargis & Sandquist (2005), Parihar et al. (2009), Marchi et al. (2010) and Saesen et al. (2010), among others.

ABSTRACT

We present results of a variability search in the intermediate-age open cluster NGC 6866 from 29 nights over two observing seasons. We find 28 periodic variables, of which 19 are newly identified. The periods of these variables, which have V magnitudes from 11.5 to 19.3 mag, range from ~48 min to 37 d. We detected several δ Scuti stars, some of which are of high amplitude, as well as γ Doradus and rotational variables, and eclipsing binaries. In order to study the physical properties of the cluster, we obtained UBVRI photometry of all the stars on a good photometric night. The radial distribution of the stellar surface density shows that the cluster has a radial extent of about 7 arcmin (~3 pc) with a peak density of 5.7 ± 0.7 stars arcmin⁻² at the cluster centre. The colour–colour diagram indicates a reddening of E(B − V) = 0.10 mag towards NGC 6866. A distance of ~1.47 kpc and an age of ~630 Myr are estimated from the colour–magnitude diagram using the theoretical isochrones of solar metallicity.

Key words: techniques: photometric – stars: variables: general – open clusters and associations: individual: NGC 6866.

At ARIES, Nainital, we have started a long-term observational survey of variable stars in unstudied or poorly studied young and intermediate-age open clusters. The purpose of this survey is to search and characterize the variable star content of these clusters and to determine their fundamental parameters. Young clusters allow the study of pre-main-sequence (pre-MS) stars and the effects of variability on the spread in cluster ages. Intermediate-age clusters can be used to study short-period variables such as δ Scuti and γ Doradus stars. Intensive uninterrupted observations over a few hours, as well as extensive observations spanning several months to years, are planned for many such clusters.

In this paper, we present a study of the intermediate-age open cluster NGC 6866 (RA = 20°03'55", Dec. = +44°09'30"; l = 79;560, b = +6:839). The cluster is in the field observed by the Kepler satellite, whose aim is to search for earth-like planets by monitoring the light variations of more than 150 000 stars in a 105-deg² field situated in the Cygnus–Lyra region. The data obtained in this mission are also used for the asteroseismic study of PVs and to investigate stellar characteristics with micro-magnitude precision and uninterrupted time-coverage (see e.g. Basri et al. 2011). The cluster NGC 6866 has not been extensively surveyed for variability. The Hipparcos and Tycho catalogues contain a few suspected variables in the cluster. Molenda-Zakowicz et al. (2009, hereinafter MOL09) obtained time-series CCD photometric observations of this cluster for 14 nights over a period of about 3 months. They found 19 variables in the field of the cluster, of which

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12 seem to be periodic variables. However, due to their limited
time-coverage, the periods and characteristics of these variables are
somewhat uncertain.

Details of the observations and data reduction are presented in
Section 2. The photometric calibration and cluster parameters are
studied in Section 3. In Section 4, we discuss the identification
of variable stars and their characteristics. This is followed by a
discussion and the conclusions.

2 OBSERVATIONS AND DATA REDUCTION

Time-series observations of stars in NGC 6866 were obtained in
the Johnson V and Cousin I bands using the 1.04-m Sampurnanand
telescope at Manora Peak, Nainital. We used a 2k × 2k CCD camera
covering a field of view of about 13 × 13 arcmin². The readout
noise and gain of the CCD are 5.3 e⁻ and 10 e⁻ ADU⁻¹. The
cluster was observed for 29 nights between 2008 September 26 and
2011 January 10 over two observing seasons. Priority was given to
V-band observations in order to increase the time-sampling in this
waveband. A total of 768 frames in the V band and 50 frames in the I
band were accumulated. Bias and twilight flat frames were taken on
a regular basis. To improve the signal-to-noise ratio, all observations
were taken in 2 × 2 binning mode (≈ 0.74 × 0.74 arcmin²). The
exposure time for each frame ranged from 30 to 200 s depending on
sky conditions and time-constraints. Typical seeing was ~2 arcsec.
In order to detect short-period variables, we observed NGC 6866
continuously for more than 4 h on three different nights with an
observing cadence of about 2.2 min. A brief log of the observations
are given in Table 1.

Table 1. Log of the CCD observations.

| Date          | Start date      | Filter | Number of frames |
|---------------|-----------------|--------|------------------|
| (yyyy mm dd) | (JD − 245 0000) |        |                  |
| 2008 09 26   | 4736.088 461    | V      | 46               |
| 2008 09 27   | 4737.071 076    | V, I   | 57.2             |
| 2008 09 28   | 4738.090 602    | V      | 54               |
| 2008 09 30   | 4740.084 549    | V      | 50               |
| 2010 09 30   | 5470.132 100    | V, I   | 3.3              |
| 2010 10 05   | 5475.112 778    | V      | 51               |
| 2010 10 06   | 5476.106 863    | V      | 100              |
| 2010 10 07   | 5477.060 637    | V      | 142              |
| 2010 10 08   | 5478.046 644    | V      | 5                |
| 2010 10 10   | 5480.104 676    | V      | 108              |
| 2010 10 12   | 5482.275 231    | V      | 3                |
| 2010 10 20   | 5490.058 611    | V      | 3                |
| 2010 10 24   | 5494.084 444    | V      | 3                |
| 2010 10 25   | 5495.117 824    | V      | 3                |
| 2010 10 26   | 5496.076 435    | V, I   | 3.3              |
| 2010 10 27   | 5497.068 206    | I      | 3                |
| 2010 10 28   | 5498.065 243    | V, I   | 3.3              |
| 2010 10 31   | 5501.105 200    | V, I   | 3.3              |
| 2010 11 01   | 5502.088 067    | V, I   | 3.3              |
| 2010 11 02   | 5503.081 900    | V, I   | 7.3              |
| 2010 11 03   | 5504.048 300    | V, I   | 61.3             |
| 2010 11 04   | 5505.111 852    | V      | 51               |
| 2010 11 30   | 5531.032 500    | V, I   | 2.2              |
| 2010 12 02   | 5533.042 700    | V, I   | 2.2              |
| 2010 12 24   | 5555.034 086    | V, I   | 2.2              |
| 2011 01 04   | 5566.040 800    | I      | 3                |
| 2011 01 05   | 5567.041 516    | V, I   | 3.6              |
| 2011 01 06   | 5568.051 100    | I      | 3                |
| 2011 01 10   | 5572.043 906    | I      | 6                |

The basic steps of image processing, which include bias subtraction,
flat-fielding and cosmic-ray removal, were performed using
IRAF. During the observations, it was not possible to keep all the
stars at the same pixel position on every night. The IRAF tasks GE-
OMAP and GEOTRAN were used to align all the images with
respect to a reference frame which was chosen so that the cluster
centre falls approximately at the centre of the observed field. In
most cases, we achieved a pixel accuracy of ~0.1 arcsec.

3 PHOTOMETRIC STUDY OF THE CLUSTER NGC 6866

3.1 Photometric calibration

Photometry was performed using the DAOPHOT II profile-fitting soft-
ware (Stetson 1987). In order to perform consistent photometry
from night to night on the aligned images, we made a master list of
2809 stars from 13 frames which have the best seeing and coverage
of the target field. It should be noted that not all stars could be
measured on every frame owing to different exposure times and sky
conditions.

To determine the extinction coefficients, colour terms and zero-
points, we used Landolt’s (1992) standard fields SA95 and PG
0231+051. These were observed on the night of 2010 November
30 in photometric sky conditions. Exposure times of 300, 300, 200,
100 and 60 s were used for U, B, V, R and I, respectively. We
acquired two frames each of NGC 6866 and PG 0231+051 and four
frames of SA95. A total of 15 standard stars with 12.68
magnitude in each band were observed during this night with airmass ranging from 1.11 to 2.04. Nine of these
stars are in SA95 and six in PG 0231+051. We used profile-fitting
photometry to extract the magnitudes using the program DAOGROW
for obtaining the curve-of-growth corrections. A linear least-squares
regression was used to the standard system to derive the following
transformation equations:

u = U + 8.13 ± 0.01 − (0.06 ± 0.01)(U − B) + (0.59 ± 0.04)X,  
b = B + 5.84 ± 0.02 − (0.02 ± 0.02)(B − V) + (0.27 ± 0.03)X,  
v = V + 5.40 ± 0.01 − (0.02 ± 0.01)(B − V) + (0.17 ± 0.02)X,  
r = R + 5.22 ± 0.01 − (0.04 ± 0.02)(V − R) + (0.09 ± 0.02)X,  
i = I + 5.63 ± 0.02 + (0.01 ± 0.01)(R − I) + (0.05 ± 0.02)X,  

where u, b, v, r and i are the aperture instrumental magnitudes and
U, B, V, R and I are the standard magnitudes and X is the
airmass. Zero-point and colour-coefficient errors are ~0.01 mag.

These equations were used to generate secondary standard stars in
the target field observed on the same night. To standardize the
data on the remaining nights, differential photometry was performed
using these secondary stars. We used a linear fit between the standard
and instrumental magnitudes on each night, assuming that most of
the stars are non-variables. We rejected stars which deviated by more
than 3σ deviations. In Fig. 1, we show the standard deviations as a
function of magnitude in the UBVRI bands. The photometric errors
were computed on the night of standardization. The typical standard
deviation is less than 0.05 mag for stars brighter than ~19 mag in the
V band.

3.2 Comparison with previous photometry

NGC 6866 has not been intensively observed in the past. UBV pho-
tolectric and photographic photometry was obtained by Hoag et al.
(1961), Johnson et al. (1961) and Barkhatova & Zakharova (1970),

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Detection of variable stars in NGC 6866

Figure 1. The photometric error of stars as a function of brightness in the UBVRI bands.

mostly for bright stars. Recently, MOL09 obtained BVI\(_c\) CCD photometry in a 12.8 \(\times\) 11.7 arcmin\(^2\) field centred on NGC 6866 using the 60-cm telescope at the Bialkow Observatory of the Wroclaw University, Poland. They observed 552 stars and derived calibrated \(B\) and \(V\) photometry. We did not compare our photometry with the older photoelectric and photographic works as these contain relatively large errors and are mostly confined to the brighter stars. We do, however, compare our results with MOL09 which, in turn, have been compared with older photoelectric and photographic measurements. We have cross-identified our stars with those of MOL09 and found 511 stars in common. Fig. 2 shows the difference, \(\Delta i\), in \(V\) and \((B - V)\) between our photometry and MOL09. A linear fit between our \(V\) magnitudes and those of MOL09 shows a magnitude dependence which can be given by the following equation:

\[
V_{\text{present}} - V_{\text{Mol}} = (0.008 \pm 0.001) \times V_{\text{present}} - (0.13 \pm 0.02).
\]

Our \(V\) magnitudes are notably brighter than MOL09 for the brightest stars, particularly towards \(V < 13\) mag. For faint stars, the \(V\) magnitudes and \((B - V)\) colours between the two photometries seem to be in agreement within their internal photometric errors.

3.3 Astrometry

To convert pixel coordinates \((X, Y)\) into celestial coordinates \((\alpha_{2000}, \delta_{2000})\), a linear astrometric solution was derived by matching about 134 bright stars in common between our catalogue and the 2MASS catalogue. We used the IRAF CCMAP and CCTRAN tasks for this purpose. Using these equations, we converted the \((X, Y)\) position into J2000 celestial coordinates for all stars in our catalogue. The typical rms scatter, as derived from the difference between calibrated and catalogued coordinates, is about 0.1 arcsec.

In Table 2, we present UBVRI photometric measurements for 2473 stars identified in the field of the cluster NGC 6866. This is only a sample listing; the full table is available in electronic form (see Supporting Information). The table contains the star ID, its celestial coordinates for J2000 and UBVRI magnitudes, and their corresponding errors. It should be noted that we were able to determine the \(U\) magnitudes for only about half of these stars owing to the low quantum efficiency of the CCD in the \(U\) band.

3.4 Cluster parameters

3.4.1 Radius

The spatial structure of the open cluster, as derived from the stellar density distribution obtained by star counts, is difficult to estimate because of the irregular shape of the cluster. However, we can obtain some information about the core and the approximate cluster radius. To determine the radial density distribution (RDD), we divided the cluster into a number of concentric annular regions centred on the cluster. The centre of the cluster was defined by the pixel coordinate \((483, 519)\) in our reference CCD frame. The cluster radius is defined as the radius where the surface density becomes approximately equal to the average density of the surrounding field. To reduce field star contamination, we only used stars brighter than 19 mag in \(V\) in determining the stellar surface density. The spacing of the annular regions was set to 40 pixels (~30 arcsec). This was chosen in such a way that each zone contains a statistically significant number of stars.

We counted the number of stars in each annular region. The number density in the \(i\)th zone is then \(\rho_i = \frac{N_i}{A_i}\), where \(N_i\) and \(A_i\) are the number of stars and the area of the \(i\)th zone, respectively. The error bars are derived assuming that the number of stars in a zone follows Poisson statistics. The radial variation of the derived density distribution is shown in Fig. 3.
Kaluzny (1992) models the projected stellar density distribution as
\[ \rho(r) = \rho_0 + \frac{\rho_0}{1 + \left( \frac{r}{r_c} \right)^2}, \]
where \( \rho_0 \) is the density at the cluster centre, \( \rho_1 \) is the field density and \( r_c \) is the core radius of the cluster. The core radius is defined as the radius where the density, \( \rho(r) \), is half of the central density, \( \rho_0 \). A fit to this function is shown by the solid line in Fig. 3. Using \( \chi^2 \) minimization, we determined the core radius and central density to be 2.0 ± 0.5 arcmin and 5.7 ± 0.7 stars arcmin\(^{-2}\), respectively. Even though our CCD frames did not encompass a large area, we were able to determine that the surface density is approximately equal to the density of the surrounding field stars at a radius of about 7 arcmin, which we take as the cluster radius.

### 3.4.2 Reddening

The reddening, \( E(B - V) \), in the cluster region can be determined using the \( (U - B) \) versus \( (B - V) \) two-colour diagram (TCD). Because only half the stars have \( U \) measurements, and also to avoid contamination by field stars, we used only stars with \( V < 17 \) mag, and \( \sigma_U \), \( \sigma_B \) and \( \sigma_V \) smaller than 0.05 mag. The resulting TCD is shown in Fig. 4. The observed cluster sequence is clearly seen, as is the turn-off which occurs at about spectral type A0. The most probable cluster members with \( V < 17.0 \) mag and \( (B - V) < 0.9 \) mag are shown by a different symbol.

We adopted the slope of the reddening vector \( E(U-B)/E(B-V) = 0.72 \). We then fitted the intrinsic zero-age main sequence (ZAMS) with solar metallicity, as given by Schmidt-Kaler (1982), to the observed MS stars. This was done by shifting \( E(B-V) \) and \( E(U-B) \) along the reddening vector (shown in Fig. 4 by the dashed line). The best match results in a mean reddening of \( E(B - V) = 0.10 \) mag for NGC 6866.

### 3.4.3 Distance and age

The identification of the cluster MS in the CMDs allows a model-dependent mass, radius and distance for each star to be determined. These are determined by fitting isochrones assuming that the star is on the MS. To derive these parameters, we constructed calibrated \( (B - V) \), \( (V - R) \) and \( (V - I) \) versus \( V \) diagrams of NGC 6866 using our data (Fig. 5). A well-defined cluster MS is clearly seen in all the CMDs. However, they are contaminated by a typical red field star population. In order to determine the age and distance of the cluster, theoretical isochrones of Girardi et al. (2002) for
Detection of variable stars in NGC 6866

Figure 3. The stellar RDP for stars brighter than 19.0 mag in the field of NGC 6866. The solid line represents the King profile and the horizontal dashed line shows the average field star density.

Figure 4. The $(U-B)$ versus $(B-V)$ diagram for stars in NGC 6866. The larger filled circles are stars which lie on or close to the MS in the CMD and which have proper motion suggesting more than 60 per cent probability of being cluster members. The dashed straight line represents the slope (0.72) and direction of the reddening vector. The solid curve represents the ZAMS from Schmidt-Kaler (1982).

Figure 5. The CMDs, $(B-V)$, $(V-R)$ and $(V-I)$ as a function of $V$, for stars in the field of NGC 6866. The solid line is the Girardi et al. (2002) isochrone (solar metallicity) for a cluster age of $\log(t) = 8.8$. A distance modulus of $V - M_V = 11.15$ and reddening $E(B-V) = 0.10$ mag were used.

solar metallicity are overplotted in the CMDs (solid lines in Fig. 5). Girardi isochrones are visually fitted by varying the distance modulus and age simultaneously while keeping the reddening fixed at $E(B-V) = 0.10$ mag (as estimated earlier using the TCD). We have assumed that the total extinction $A_V = 3.1 \times E(B-V)$. The best-fitting model of the cluster gives a reddening-free distance modulus $(V_0 - M_V) = 10.84$ mag and an age of $\log(t) = 8.8$ yr.

The physical parameters determined for the cluster NGC 6866 in this study are summarized in Table 3. We also compare our results with those given by Kharchenko et al. (2005). In general, our values are in good agreement. However, we obtained a significantly smaller core radius and reddening than Kharchenko et al. (2005).
4 VARIABLE STARS IN THE CLUSTER NGC 6866

4.1 Selection criteria to identify variables

After excluding observations taken under poor sky conditions, we considered only 718 photometric observations in the V band and 47 in the I band for the variability search. In order to search for variable stars in the target field, the time-series V-band magnitudes of all stars are subjected to the periodicity analysis explained in the following section. A star was analysed for variability only if it met the following criteria:

(i) The star should not be within 10 pixels from the edge of any frame.
(ii) The magnitude of the star should have a standard deviation less than three times the mean error in the corresponding magnitude bin.
(iii) The stellar magnitude needs to be measured in at least 100 frames.

4.2 Periodicity analysis

We used the Lomb–Scargle periodogram (Lomb 1976; Scargle 1982) to estimate the period of a variable star. This method computes the Fourier power spectrum by fitting sine and cosine terms over a large number of frequencies in the given frequency range and is applicable to unevenly sampled data. The period was derived using only the V-band data because of the better sampling in this filter. In some cases, a few points were removed because either they were deviated by more than 0.2 mag in two sequential observations or strongly deviated from the mean magnitude. To search for periodic variables, we have given a range of periods from 0.01 to 100 d as our total time-length was about 100 nights in 2010. The large range of period search was chosen because the Lomb–Scargle method uses a period search in the logarithmic time-scale and hence shallower at longer periods. However, we have not considered any period beyond 50 d, which is about half of the total observing time-span. We noted that many spurious variables were found with periods which are harmonics or daily aliases of each other. These stars were rejected. Only stars that lied in the magnitude range V < 19.5 were considered for the variability search as photometric magnitudes have large errors towards fainter ends. Further, we have not considered the 2008 observing data for the brighter stars having V < 12.5 mag which shows large uncertainty in the photometric measurements.

After these selection criteria, we visually inspected the light curves of the remaining stars for periodic variation and found 28 variable stars. A phased light curve was derived for each star using an estimated period. A phase-folded light curve, binned in intervals of 0.01 phase, was constructed by taking the average of the magnitudes in these phase bins. It was noted that in some periodic variables, particularly in binary stars, the period-finding routine gives a ‘best-fitting’ period that actually corresponds to half the orbital period. To detect such variables, we inspected the light phased at twice the period given by the period-finding algorithm. For example, ID 248 gives a period of 0.217 d using the Lomb–Scargle algorithm, but by visual inspection, we found that the true period is 0.434 d because the light curve has two unequal minima. In this way, we found seven stars which were better represented with twice the period given by the Lomb–Scargle periodogram.

Among the 28 periodic variables identified in this study, 19 are newly detected. Table 4 lists the identification number of variable stars, celestial coordinates, periods, and their membership probabilities. We also give the intensity-averaged mean magnitude and amplitude of brightness variation in the V band. The amplitude was estimated as the difference between the median values of the upper and lower 15 per cent magnitude values of the light curve (cf. Herbst et al. 2002; Messina et al. 2010). In the last two columns, we give a possible class of variability from our analysis and corresponding identification in MOL09, and period if the star has already been identified. The V-band phased light curves of these variables are shown in Fig. 6.

Having the lesser number of data points, smaller amplitude of variation and larger photometric error in the I band in comparison to the V band, we do not use I-band data in our analysis. However, I-band phased light curves for all the 28 variables, along with their time-magnitude photometric data in the V and I bands, are available in electronic form (see Supporting Information). In Fig. 7, we provide a finding chart of an ~13 × 13 arcmin² field of the cluster marking the variable stars.

4.3 Comparison with other catalogues and previously known variables

No time-series photometric observations of NGC 6866 have been published prior to MOL09. They detected 19 variables, 12 of which were periodic variables. Out of the 19 variable stars, we are able to find periodicity in 12 variables, while two irregular variables, V15 (ID 53) and V16 (ID 89), in their list have also shown irregular variation in our data. The remaining five variables from MOL09 are not included in our list of variable stars. The variable V2 (ID 30) is reported as a δ Scuti star with an amplitude variation of only 0.006 mag. We are unable to detect such a low-amplitude variation in this bright (V ~ 12.3 mag) star owing to the uncertainties in our data towards the brighter end. The star V08 (ID 92) is heavily blended by two nearby stars brighter than this star. Though the light curve shows a significant flux variation in our data, it is not ellipsoidal in nature as reported by MOL09. Since this is a contaminated star, its variability is highly susceptible to include it in our list of variable stars. The star V10 (ID 82) is listed as an eclipsing binary (EB) in their catalogue. For a period of 1.916 d, as reported by MOL09 for this star, we should be able to confirm the variations because our observations extend over a longer time-span. However, we cannot confirm the eclipsing nature of this star from the present data. Two stars in their catalogue, V17 and V19, which were classified as irregular variables lie close to the edges of our frames. Since their reliable photometry could not be determined in at least 100 frames, we exclude them from our list of variable stars.

It can be seen from Table 4 that there is a significant difference between our periods and those of MOL09 for five variables. We therefore created phase-folded light curves using periods from

Table 3. A comparison of the fundamental parameters of NGC 6866 from our study with that of Kharchenko et al. (2005).

| Cluster parameter | This study | Kharchenko et al. (2005) |
|-------------------|------------|-------------------------|
| R_{core} (arcmin) | 2.0        | 4.2                     |
| R_{cluster} (arcmin) | 7.0        | 8.4                     |
| Mean E(B − V)   | 0.10       | 0.17                    |
| V − M_V         | 11.15      | 11.33                   |
| log(age/yr)     | 8.8        | 8.68                    |
| Distance (kpc)  | 1.47       | 1.45                    |
MOL09 for each of the variables in common and compared them by eye with our phased light curves. We do not see any systematic variation for these variables in terms of their period apart from the δ Scuti V3 which could have either period. The variable V4 (ID, 0.049) is a faint star (V ~ 19.1 mag) which lies close to the edge of our CCD chip in most of the frames, hence could be detected only in 111 frames. We therefore caution that our estimated period may not be very reliable due to its small number of data points.

4.4 Cluster membership of the variable stars
We assigned a probability of cluster membership to a star on the basis of its angular distance from the cluster centre, its location in the CMD and its proper motion with reference to the mean proper motion of the cluster. The spatial probability (Psp), which gives the position of the star in the field of the cluster, was determined as 1 - r/rrc, where r is the angular distance of the star from the cluster centre and rrc (7 arcmin) is the radius of the cluster.

The photometric probability (Pph) was computed with reference to the blue and red limits in the B - V versus V diagram. The blue sequence was defined using empirical ZAMS colours (Schmidt-Kaler 1992) shifted in magnitude and colour by 11.15 and 0.10 mag, respectively, to visually match the cluster sequence. The red sequence was defined by a shift of -0.75 mag in V and a shift of 0.042 in B - V in order to account for unresolved MS binaries (Maeder 1974; Kharchenko et al. 2004). Stars with B - V colours lying within the binary sequence of the MS were assigned Pph of 1 and are probable members of the cluster, while stars deviating along either direction were assigned a probability as exp (-0.5 x [Δ(B - V)/σ(B - V)])², where Δ(B - V) is the difference between colours from blue or red colour limits and σ(B - V) is the photometric error in colour.

The proper motion probability (Ppm) was calculated using the catalogue of Roeser, Demleitner & Schilbach (2010) which lists positions in the International Celestial Reference System (accuracy: 80–300 mas) and absolute proper motion (accuracy: 4–10 mas yr⁻¹) of about 900 million stars, derived from the optical USNO-B1.0 and near-infrared 2MASS catalogues. A cross-match of our photometry (2473 point sources) with that of Roeser et al. (2010) gave 1772 stars in common within a radius of 500 mas. For these stars, a scatter plot of the proper motion in right ascension (μα) versus that in declination (μδ) is given in Fig. 8. Unlike other nearby well-studied open clusters (see e.g. Bellini et al. 2010), no clear trend separating members and field stars is seen. We therefore computed the mean proper motions of the cluster with V < 17 mag, Pph = 1 and Ppm > 0.5, which gives the mean proper motions μα = -3.47 ± 0.41 mas yr⁻¹ and μδ = -3.30 ± 0.35 mas yr⁻¹, respectively.¹ The computations were done iteratively using a clipping algorithm and the uncertainties denote rms deviations. Pph for each star was computed following Kharchenko et al. (2004) as

1 The mean proper motions of NGC 6866 are consistent with the values (-3.86 ± 0.16, -4.63 ± 0.17) estimated by MOL09 who calculated an older catalogue of Roeser et al. (2008) which lists proper motion data of only brightest (V < 14 mag) stars.
Figure 6. $V$-band phased light curve for the 28 variable stars identified in this study. The phase is plotted twice and shifted in such a way that the light minimum falls near to zero phase.
Detection of variable stars in NGC 6866

Figure 7. Finding chart for the variable stars in the field of NGC 6866. The size of points signifies the magnitude of the stars. The 28 periodic variables identified in this study are additionally indicated with the open circles.

\[ \exp[-0.25\left(\sigma_{\mu}^2 + \sigma_{\bar{\mu}}^2\right)] \]

where \(\sigma_{\mu}^2 = \sigma_{\mu\mu} + \sigma_{\bar{\mu}\bar{\mu}}\) and \(\sigma_{\bar{\mu}}^2 = \sigma_{\mu\bar{\mu}} + \sigma_{\bar{\mu}\mu}\). We could thus assign \(P_{ph}\) for 1949 stars in common with the R10 catalogue within a search radius of 1 arcsec.

The probabilities \(P_{sp}, P_{ph}, P_{pm}\) are listed in Table 2.

On the basis of spatial probability, stars found in the core of the cluster NGC 6866 (\(R_{core} = 2.0 \pm 0.5\) arcmin), for which \(P_{sp}\) is greater than 0.71 \(\pm 0.06\), could be cluster members. The star having \(P_{ph} = 1.0\) might belong to the cluster on the basis of photometric probability, and stars with \(P_{pm} > 60\) per cent (1σ) most probably belong to the cluster on the basis of proper motion criteria. Five variable stars detected in this study, which satisfy all the three probability criteria, are considered as definite members of the cluster NGC 6866. Nine stars which satisfy two criteria are considered as likely members, while other nine stars which satisfy either only one criterion or have \(P_{pm} < 60\) per cent are considered as unlikely members. Five stars that do not follow any membership criteria are considered as definite field stars. Membership probabilities and their status as a cluster member are given in Table 4.

4.5 Characterization of the variable stars

We assessed the classifications of variable stars by manually comparing their phase-folded light curves with template light curves of different classes of variables. Our classification is primarily based on period, shape of the light curves and location of the star in the
CMD. In Fig. 9, we show the position of the variable stars in the $(B - V)_{0} - M_{V}$ plane of the cluster. The intrinsic magnitude and colour of the variable stars are determined using the distance modulus $(m - M)_{0} = 11.15$ mag and extinction $E(B - V) = 0.10$ mag as estimated in our study. The dashed line is the ZAMS taken from Schmidt-Kaler (1982). In order to draw the classical instability strip in the CMD, we transformed the theoretical instability strip boundaries of Pamyatnykh et al. (2000) into our observational plane using colour–$T_{\text{eff}}$ relations from VandenBerg & Clem (2003). The characterization of the variable stars detected in our study is summarized as follows.

4.5.1 Previously identified variables

ID 27 is classified as a δ Scuti star by MOL09. In the CMD, this star is located within the δ Scuti instability strip, justifying their classification. ID 39 and ID 94 are reported as γ Doradus variables. The location of ID 39 is towards the blue edge of the δ Scuti instability strip, but its period suggests that it is a γ Doradus star. This makes it an interesting target for future observations. ID 81 is classified as an irregular variable in MOL09. We found a periodicity of 1.24 d in the present data; however, our observations did not give a uniform sampling at all the phases; hence, there may be little uncertainty in the period. This star along with ID 94 falls in the γ Doradus instability strip in the Hertzsprung–Russell diagram which suggests that these stars belong to the γ Doradus class of variables. MOL09 classified IDs 74, 487, 494 and 1274 as W Ursae Majoris (W UMa) type variables. Our light curves support their classification for IDs 487, 494 and 1274; however, the light curve of ID 74 looks like an ellipsoidal variation. ID 248 has an unusual light curve. This star is reported as an ellipsoidal variable, but it does not have the typical light curve of interacting binaries. It shows light minima of equal depth instead of light maxima. Such a strange light curve might arise if we view an interacting binary in a highly-eccentric orbit close to pole-on. The variation in brightness is a result of change in the size of the stars as they start approaching the periastron. IDs 239 and 253 are classified as irregular variables by MOL09, but our phased light curves show clear periodic variability. ID 239, which is an unlikely member of the cluster, is the reddest $(B - V = 2.09, V - I = 3.44)$ and longest period (~37 d) variable identified in this study. This star is most likely a background red giant, and variability in these stars shows considerable periodicity in their light variation, accompanied or sometimes interrupted by various irregularities as seen in their light curve. We therefore classified this star as a semi-regular variable. ID 253 seems to be a rotational variable.

ID 47 is reported as a 0.066-d δ Scuti variable (V1) by MOL09. Though this star falls in the δ Scuti instability strip in the CMD of our data, the shape of the light curve is not a typical δ Scuti variation. Moreover, our study finds a period of 0.275 d and magnitude variation of 0.041 mag for this star which is significantly higher in comparison to MOL09. While the proper motion probability for this star is reported as 72 per cent by MOL09, this study gives a probability of only 55 per cent. Based on the spatial distribution, this star has only 27 per cent probability of belonging to the cluster. Therefore, despite this star falling in the δ Scuti instability strip in the CMD of the cluster, present observations suggest that the star is unlikely a cluster member and highly susceptible to being a δ Scuti variable.

4.5.2 New variables

A total of 16 new variables were detected from the time-series data analysis of NGC 6866. We classify ID 36, a likely member of the cluster, as a δ Scuti variable as it is located in the δ Scuti instability strip. ID 58, which is a field star, shows a light variation similar to a γ Doradus variable. IDs 16, 20 and 191 show similar light curves. They could be binary stars, though further data are needed to ascertain their exact nature of variability. ID 158 seems to be an EB of Algol (EA) type, where the primary and secondary eclipses are clearly seen in the phased light curve. IDs 221 and 253 show similar light curves. The periods and amplitudes are also similar. ID 221 is a likely member and ID 231 is a confirmed member of
Detection of variable stars in NGC 6866

Figure 9. The \((B - V)_{0}\) versus \(M_V\) CMD for NGC 6866. The thick dashed line shown in blue is the ZAMS corresponding to \(V - M_V = 11.15\) and \(E(B - V) = 0.10\) mag, while the red dashed line indicates a shift in magnitude and colour due to binarity. The positions of the 28 periodic variables are also shown in the CMD. The standard errors in colour and magnitude at various magnitude ranges are given on the right-hand side of the panel. The thin solid lines represent the instability strip for \(\delta\) Scuti stars, while the thick solid lines represent the same for \(\gamma\) Doradus stars.

the cluster based on their membership probabilities. Both stars lie on or near the MS. These stars are placed in the group of PVs. IDs 332 and 349 look like a semi-regular or long-period variable (LPV). ID 444 has a periodicity of \(\sim 16.3\) d and displays the signature of primary and secondary eclipses. More observations will be needed to see light variations at all phases for this LPV; nevertheless, we classify this star as a \(\beta\) Lyrae type binary (EB) based on present observations. IDs 1077, 1088, 1292, 1421 and 1583 have periods similar to \(\delta\) Scuti stars, but have significantly large amplitudes, suggesting that these stars could be high-amplitude \(\delta\) Scuti stars (HADS).

This study along with MOL09 classified IDs 487, 494 and 1274 as W UMa-type variables which are known to obey a period-luminosity–colour (PLC) relation (Rucinski 2004) as follows:

\[
M_V = -4.44 \log(P) + 3.02(B - V)_{0} + 0.12, \quad \sigma = 0.25\text{ mag}
\]

where \((B - V)_{0}\) is the intrinsic colour index and \(P\) is the orbital period in days. We derived the apparent distance modulus \((m - M)_V\) of each W UMa star from the absolute magnitude \(M_V\) determined using the above relation and their mean \(V\) magnitudes. A reddening of \(E(B - V) = 0.10\) was assumed. Of the three W UMa variables, ID 487 is the most interesting. It has a very high proper motion probability of 0.85, spatial probability of 0.76 and photometric probability of 1.0, and hence considered a confirmed member of the cluster. However, \((m - M)_V\) of this star is estimated as 12.53 mag from the W UMa PLC relation. This is 1.38 mag fainter than the apparent distance modulus of the cluster. Since the period and colour of this star are quite robust, a large value of \((m - M)_V\) suggests that either this star is not a cluster member or it does not belong to the class of W UMa variables, hence not following the above relation. This star needs further attention to ascertain its true membership and nature of variability. Other two stars, IDs 494 and 1274, have zero proper motion and no proper motion information available, respectively. Though both of them fall in the CMD, their spatial position in the target field is quite far from the cluster centre. Furthermore, IDs 494 and 1274 are fainter by 0.94 and 2.03 mag, respectively, than the estimated distance modulus of the cluster. This makes these two W UMa stars unlikely members of the cluster.

5 SUMMARY

The work presented here is the first paper of our series of papers on the detection and characterization of variable stars in young and intermediate-age open clusters. In this work, we have presented a search for variable stars in the cluster NGC 6866. We found 28 variables in the period range 0.03 d (\(\sim 48\) min) to 37 d, and confirmed the irregularity in the light curves of other two irregular variables
reported by MOL09. Among them, 16 are newly discovered periodic variables. We also determined the period for three other variables which were reported as irregulars in MOL09. Prior to this study, the shortest period variable detected in NGC 6866 was a 13-mag δ Scuti star with a period of 1.6 h. Since we have carried out continuous observations in the V band for more than 4 h on three nights, it has enabled us to find a variable star with period as short as 48 min. In the field of NGC 6866, we did not find any variable star which shows variations in excess of 0.5 mag. In comparison with previous studies, we report more than twice the number of periodic variables in the field of NGC 6866.

In this study, we have analysed the membership of stars on the basis of their distance from the cluster centre, position in the CMD, and their proper motion, wherever available. The membership probability of stars on the basis of all the three criteria was estimated. Our analysis of 28 periodic variables suggests that 14 variables are either confirmed members or likely members of the cluster, while the remaining 14 variables are either field stars or unlikely members of the cluster. Based on the shape and period of light variations, together with the colour and amplitude, we found several δ Scuti, γ Doradus and rotational variables, and EBs. Few variables could not be classified with precision and more photometric observations are needed to ascertain the exact nature of these stars. Further multicolour photometry and spectroscopic observations of these stars will help us to determine their parameters such as mass and radius.

We also provide calibrated $UBVRI$ photometry of 2473 stars down to $V \sim 21.5$ mag. These data were used to determine the physical parameters of the cluster and derive the cluster radius from the stellar density profile, and the extinction, distance and age from the colour–colour diagram and CMD. The basic parameters of the cluster NGC 6866 is obtained through isochrone fitting, giving $\log(t) = 8.8$ yr, a distance modulus of $(m - M)_0 = 10.84$ mag, and extinction $E(B - V) = 0.10$ mag. The radial distribution of the stellar surface density indicates that the core and cluster radius is extended up to about 2 and 7 arcmin, respectively, with a peak density of $5.7 \pm 0.7$ star arcmin$^{-2}$ at the cluster centre.

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REFERENCES

Barkhatova K. A., Zakharova P. E., 1970, Utschenie Zapisky, Urals Univ., 93, 3
Basri G., Walkowicz L. M., Batalha N., 2011, AJ, 141, 20
Bellini A., Bedin L. R., Pichardo B., Moreno E., Allen C., Pietro G., Anderson J., 2010, A&A, 513, 51
Girardi L., Bertelli G., Bressan A., Chiosi C., Groenewegen M. A. T., Marigo P., Salasnich B., Weiss A., 2002, A&A, 391, 195
Hartig J. R., Sandquist E. L., 2005, AJ, 130, 2824
Herbst W., Bailey-Jones C. A. L., Mundt R., Meisenheimer K., Wackermann R., 2002, A&A, 396, 513
Hoag A. A., Johnson H. L., Iriarte B., Mitchell R. I., Hallam K. L., Sharpless S., 1961, Publ. US Nav. Obs., 17, 343
Johnson H. L., Hoag A. A., Iriarte B., Mitchell R. I., Hallam K. L., 1961, Bull. Lowell Obs. No. 113, V, 133
Kaluzny J., 1992, Acta Astron., 42, 29
Kharchenko N. V., Piskunov A. E., Roeser S., Schilbach E., Scholz R.-D., 2004, Astron. Nachr., 325, 740
Kharchenko N. V., Piskunov A. E., Roser S., Schilbach E., Scholz R.-D., 2005, A&A, 438, 1163
Landolt A. U., 1992, AJ, 104, 340
Lomb N. R., 1976, Ap&SS, 39, 447
Maeder A., 1974, A&A, 32, 177
Marchi F. D., Poretti E., Montalto M., Desidera S., Pietro G., 2010, A&A, 509, A17
Messina S., Distefano E., Parihar P., Kang Y. B., Kim S.-L., Rei S.-C., Lee C.-U., 2008, A&A, 483, 253
Messina S., Parihar P., Koo J.-R., Kim S.-L., Rei S.-C., Lee C.-U., 2010, A&A, 513, A29
Molenda Zakowicz J., Kopacki G., Steslicki M., Narw Adidas, 2009, Acta Astron., 59, 193 (MOL09)
Pamyatnykh A. A., 2000, in Breger M., Montgomery M., eds, ASP Conf. Ser. Vol. 210, Delta Scuti and Related Stars. Astron. Soc. Pac., San Francisco, p. 215
Parihar P., Messina S., Distefano E., Shantikumar N. S., Medhi B., 2009, MNRAS, 400, 603
Roeser S., Demleitner M., Schilbach E., 2010, AJ, 139, 2440
Rucinski S. M., 2004, New Astron. Rev., 48, 703
Saesen S. et al., 2010, A&A, 515, A16
Scargle J. D., 1982, ApJ, 263, 385
Schmidt-Kaler Th., 1982, in Scaifers K., Voigt H. H., eds, Landolt/Bornstein, Numerical Data and Functional Relationship in Science and Technology. Springer-Verlag, Berlin, p. 14
Stetson P. B., 1987, PASP, 99, 191
VandenBerg D. A., Clem J. L., 2003, AJ, 126, 778

SUPPORTING INFORMATION

Additional Supporting Information may be found in the online version of this article.

Table 2. $UBVRI$ photometric catalogue of 2473 stars detected in the field of the cluster NGC 6866. The respective columns give star ID, magnitude in $U$, error $(U)$, $B$, error $(B)$, $V$, error $(V)$, $R$, error $(R)$, $I$, error $(I)$, spatial probability, photometric probability and proper motion probability.

| ID | $U$ magnitude | $U$ error | $B$ magnitude | $B$ error | $V$ magnitude | $V$ error | $R$ magnitude | $R$ error | $I$ magnitude | $I$ error |
|----|--------------|-----------|--------------|-----------|--------------|-----------|--------------|-----------|--------------|-----------|
| 1  | 1.0          | 0.01      | 0.0          | 0.01      | 0.0          | 0.01      | 0.0          | 0.01      | 0.0          | 0.01      |
| 2  | 2.0          | 0.02      | 0.02         | 0.02      | 0.02         | 0.02      | 0.02         | 0.02      | 0.02         | 0.02      |

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