Variable stars in the field of the old open cluster Melotte 66

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ABSTRACT

We report the results of photometric monitoring of the Melotte 66 field in BVI filters. 10 variables were identified with nine being new discoveries. The sample includes eight eclipsing binaries of which four are W UMa type stars and one star is a candidate blue straggler. All four contact binaries are likely the members of the cluster based on their estimated distances.

10 blue stars with $U - B < -0.3$ were detected inside a 14.8 × 22.8 arcmin$^2$ field centred on the cluster. Time series photometry for seven of them showed no evidence for any variability. The brightest object in the sample of blue stars is a promising candidate for a hot subdwarf belonging to the cluster. We show that the anomalously wide main sequence of the cluster, reported in some earlier studies, results from a combination of two effects: variable reddening occurring across the cluster field and the presence of a rich population of binary stars in the cluster itself. The density profile of the cluster field is derived and the total number of the member stars with $16 < V < 21$ or $2.8 < M_V < 7.8$ is estimated conservatively at about 1100.

Key words: binaries: close – open clusters and associations: individual: Melotte 66.

1 INTRODUCTION

Melotte 66 ($\alpha = 07^h26^m21.9^s, \delta = -47\degree41\arcmin19\arcsec$, J2000) belongs to a small sample of old galactic open clusters (Kassis et al. 1997). It is located at a relatively large Galactic latitude ($l = 259\degree6, b = -14\arcmin3$). A pioneering study based on the photographic photometry was conducted by Eggen & Stoy (1962). Subsequent investigations based on photographic and photoelectric photometry (Hawarden 1976; Anthony-Twarog, Twarog & McClure 1979) were followed by several papers published in the last two decades of the 20th century. Kassis et al. (1997) used deep $VI$ photometry to derive an age of 4 ± 1 Gyr and distance modulus ($m - M)_0 = 13.2^{+0.3}_{-0.1}$. Anthony-Twarog, Twarog & Sheeran (1994) used $vbyH\beta$ data to discuss the possible causes of an atypically wide-cluster main sequence which was originally noted by Anthony-Twarog et al. (1979). They excluded differential reddening across the cluster field as a cause of this effect.

The cluster stands out from the sample of the known old open clusters in its exceptionally low metallicity. Twarog, Anthony-Twarog & Hawarden (1995) derived [Fe/H] = −0.53 ± 0.08 based on $UBV$ photometry of turn-off stars. Friel & Janes (1993) obtained [Fe/H] = −0.51 ± 0.11 from a spectroscopic analysis of four giants while Gratton & Contarini (1994) derived [Fe/H] = −0.38 ± 0.15 from high-resolution spectra of two giants.

This paper is a contribution to the systematic search for short period variables in open clusters conducted by our group over the last two decades. One of the goals is to establish a relation between age and a relative frequency of occurrence of contact binaries in stellar clusters. A summary of some of our earlier results can be found in Rucinski (1998). Here, we report the results of a survey for variable stars in the field of Melotte 66 and also present deep CCD $UBVI$ photometry for the cluster.

2 OBSERVATIONS AND REDUCTIONS

The field of Melotte 66 was surveyed for variable stars with the 1-m Swope telescope at Las Campanas Observatory. The observations were collected on a total of 21 nights during four observing runs during the period 1992 February to 1992 March. Two different cameras were used: a 1024 × 1024 Tektronics CCD with a scale of 0.61 arcsec pixel$^{-1}$ (TEK2 camera with a 10.4 × 10.4 arcmin$^2$ field) and a 2048 × 2048 Ford Aerospace CCD with a scale 0.435 arcsec pixel$^{-1}$ (FORD2 camera with a 14.8 × 14.8 arcmin$^2$ field).

Most of the images were collected with a $V$ filter with exposure times ranging from 60 to 480 s with a median value of 420 s. Exposures were also obtained in the $B$ and $I$ bands. A summary log of the observations is listed in Table 1. An additional set of $UBVI$ observations to calibrate the photometry and to construct a colour–magnitude diagram (CMD) for the cluster field was obtained on the nights of 1999 November 17–1999 November 20 (UT) using the 2048 × 3150 SITE3 camera. With a scale of...
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Table 1. Summary of Melotte 66 observations.

| Run     | Dates       | Nights no. | Number of exposures | Median seeing in V filter |
|---------|-------------|------------|---------------------|--------------------------|
| FORD2-1| 1992.02.03–08| 5          | 8 59                | –                        |
| FORD2-2| 1992.03.20–24| 3          | – 12 44             | 1.2 arcsec               |
| TEK2-1  | 1992.02.09–16| 7          | – 134 5             | 1.5 arcsec               |
| TEK2-2  | 1992.03.13–18| 6          | 68 66               | –                        |

Table 2. Equatorial coordinates of variables and a UV bright star in the field of Melotte 66.

| ID | $\alpha_{2000}$ [h] | $\delta_{2000}$ [°] | $r$ [arcmin] |
|----|---------------------|---------------------|--------------|
| V1 | 111.59 873          | −47.70 060          | 0.78         |
| V2 | 111.53 339          | −47.62 291          | 4.58         |
| V3 | 111.61 123          | −47.67 409          | 1.18         |
| V4 | 111.57 849          | −47.69 664          | 0.71         |
| V5 | 111.56 815          | −47.64 329          | 2.87         |
| V6 | 111.72 366          | −47.76 692          | 7.12         |
| V7 | 111.56 230          | −47.72 299          | 2.38         |
| V8 | 111.54 562          | −47.71 756          | 2.54         |
| V9 | 111.71 073          | −47.75 736          | 6.35         |
| V10| 111.63 718          | −47.68 840          | 1.85         |
| C1 | 111.57 537          | −47.74 433          | 3.31         |

3 RESULTS FOR VARIABLES

2.1 Photometric calibration

We have used the data collected on the night of 1999 November 18 to calibrate our photometry. Observations of the cluster field were bracketed by observations of three Landolt fields containing a total of 28 standard stars with BVI magnitudes (Landolt 1992; Stetson 2000) and 19 stars with $U$ magnitudes (Landolt 1992). The $T$ Phe field was observed twice while each of the RU 149 and RU 152 fields was observed once. Standards were observed at air masses spanning the range 1.12–1.24 while Melotte 66 was observed at an air mass of about 1.1. Average extinction coefficients for Las Campanas were assumed in determining the linear transformations between the instrumental and the standard system. The total uncertainties of the zero-points of our photometry are about 0.02 mag for $BVI$ filters and about 0.1 mag for the $U$ filter. These uncertainties include errors in the aperture corrections derived for the frames of Melotte 66. The relatively poor quality of the $U$-band transformation can be explained by large differences in the UV spectral responses of the SITE3 CCD camera and the RCA 1P21 photomultiplier defining the $UBV$ system (Johnson 1963). The median values of the formal internal errors of our photometry for the cluster range from $\sigma_V = 0.010$ and $\sigma_{V-I} = 0.021$ at $V = 15.5$ to $\sigma_V = 0.018$, and $\sigma_{V-I} = 0.027$ at $V = 19.5$.

We compare our $V$ photometry with the data taken from Kassis et al. (1997) in Fig. 2. The mean difference (in the sense of ‘our’ measurements minus ‘theirs’) is $-0.005 \pm 0.001$ and $-0.023 \pm 0.001$ for $V$ and $V-I$, respectively. There is no clear colour dependence of the residuals for the $V$ magnitudes. There are some systematic trends for the $V-I$ residuals.

3 RESULTS FOR VARIABLES

Table 3 lists some basic characteristics of the light curves of variables V1–V10. For each star, we list $V$ magnitude and colours measured at maximum light. The full range of observed magnitudes in the $V$ band is listed as $\Delta V$. The location of the variables on the cluster $V/B - V$ and $V/V - I$ diagrams is shown in Fig. 3 while their light curves are presented in Figs 4–6. Stars V3–V10 show periodic variability and can be classified as eclipsing binaries (EC). Moreover, stars V4, V6, V8 and V9 are likely contact binaries (EW) based on their periods, colours and light curves. Variables V1 and V2 are located on or near the cluster subgiant branch while eclipsing binary V3 is a candidate blue straggler. Three other non-contact binaries are located on or slightly above the cluster main sequence. Unfortunately, none of these seems to be a good candidate for spectroscopic follow-up aimed at the determination of cluster distance and age. V5 shows shallow eclipses while V10 is too faint for high-resolution spectroscopy. The light curve of V7 is well defined and its shape indicates that the system is a likely semidetached Algol.

All variables are located inside the cluster radius which we estimate at 9.2 arcmin in Section 4. An examination of the angular

0.435 arcsec pixel$^{-1}$, this camera provides a field of view of $14.8 \times 22.8$ arcmin$^2$. Several exposures of different length were obtained in each of the four filters. All images were corrected for the known non-linearity of the SITE3 camera using the procedure described in Hamuy et al. (2006).

Preliminary processing of the CCD frames was done with standard routines in the IRAF-CCDPROC$^1$ package. Profile photometry was extracted using the DAOPHOT/ALLSTAR package (Stetson 1987). For each camera/filter combination a ‘master’ frame was selected. This was used to create a reference list of objects to be measured in the fixed-position mode on the remaining frames. Instrumental magnitudes were transformed to the system defined by the master frame. The resulting data bases were searched for variable objects using codes using the analysis of variance (AoV) statistic (Schwarzenberg-Czerny & Beaulieu 2006). AoV periodograms were calculated for periods spanning the range from 0.05 to 20 d. After the rejection of some spurious detections, we ended up with a list of 10 certain variable stars. Nine of these are new discoveries while one is an eclipsing binary V345 Pup reported by Kaluzny & Shara (1988). Equatorial coordinates of the variables were determined using 1651 stars from the USNO A-2 catalogue (Monet 1998) which were identified on the $V$-band image obtained with the SITE3 camera. These coordinates are listed in Table 2 along with the coordinates of a ultraviolet (UV) bright star labelled C1 (see Section 3.1). The last column of Table 2 gives the angular distance from the cluster centre as determined from our data [RA(2000) = 07°26′21″9 and Dec.(2000) = $-47°41′19″$]. In Fig. 1, we present finding charts for the stars listed in Table 2.

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Variable stars in the field of Melotte 66

Figure 1. Finding charts for variables V1–V10 and for the UV bright star C1. Each chart is 1 arcmin on a side, with east to the left and north to up.

Figure 2. Residuals of \( V \) and \( V-I \) for this work and Kassis et al. (1997) as a function of \( V-I \).

Figure 3. CMDs of Melotte 66 field with marked positions of variables.

distances listed in Table 2 shows that most of the variables are in the central part of Melotte 66. There is radial velocity information available for only one of the variables. Collier & Reid (1987) list \( V_r = 75 \pm 7 \text{ km s}^{-1} \) for \( V2 = 1210 \) based on a single observation. The mean value for 59 stars considered to be cluster members is \( 44 \pm 12 \text{ km s}^{-1} \). This seems to indicate that \( V2 \) has a low probability to be a radial velocity member of Melotte 66. However, this evidence is weak as the radial velocity of \( V2 \) is likely to be variable.

Table 3. Parameters of variables from the field of Melotte 66.

| ID | \( V_{\text{max}} \) | \( (V-I)_{\text{max}} \) | \( (B-V)_{\text{max}} \) | \( \Delta V \) | \( P \) [d] | \( T_0 \) HJD 2448000+ | Remarks |
|----|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|---------|
| V1 | 14.626          | 1.29            | 1.10            | 0.15            | \( P \sim 8^d \) | –               | Periodic? |
| V2 | 15.884          | 1.18            | 0.99            | 0.1             | –               | –               | –       |
| V3 | 16.341          | 0.45            | 0.37            | 0.30            | 0.8015 (2)      | 657.7128        | Ecl     |
| V4 | 16.65           | 0.79            | 0.61            | 0.17            | 0.4020 (17)     | 656.6764        | Ecl-EW  |
| V5 | 17.03           | 0.85            | 0.65            | 0.15            | 0.7413 (2)      | 658.7648        | Ecl     |
| V6 | 17.24           | 0.96            | –               | 0.12            | 0.6974 (3)      | 657.6511        | Ecl-EW  |
| V7 | 17.519          | 0.86            | 0.64            | 1.78            | 0.5942 (1)      | 656.5508        | Ecl=V3-45 Pup |
| V8 | 18.16           | 0.71            | 0.55            | 0.16            | 0.32903 (6)     | 655.5672        | Ecl-EW  |
| V9 | 20.11           | 1.29            | –               | 0.49            | 0.2386 (4)      | 656.7105        | Ecl-EW  |
| V10| 20.2            | 1.1             | 1.0             | 0.9             | 0.8882 (9)      | 668.7426        | Ecl     |
Some indication of membership status can be provided for four contact binaries. We have applied the absolute brightness calibration established by Rucinski (2000) to estimate their absolute magnitudes. The calibration gives $M_V$ as a function of unreddened colour and orbital period. We adopted reddening of $E(V - I) = 0.22$ resulting from $E(B - V) = 0.16$ advocated by Anthony-Twarog et al. (1994). Using de-reddened $V - I$ colours and periods listed in Table 3, we obtained $M_V = 3.51, 3.07, 3.79$ and 6.33 for V4, V6, V8 and V9, respectively. The apparent distance moduli of these four variables follow from the observed values of $V_{\text{max}}$. We obtained $(M - m)_V = 13.14, 14.17, 14.36$ and 13.78 for V4, V6, V8 and V9, respectively. These values can be compared with the apparent distance modulus of the cluster of $(M - m)_V = 13.75$ as measured by Kassis et al. (1997). The formal error of $M_V$ obtained from

**Figure 4.** $BVI$ phased light curves of periodic variables V3, V4, V5, V7, V8 and V10.

**Figure 5.** Phased light curves of periodic variables V6 and V9.
Rucinski’s calibration is about 0.3 mag and so the estimated distance moduli are consistent with cluster membership for all four contact binaries. This conclusion holds if we adopt $E(B-V) = 0.23$ for the cluster reddening as implied by maps of Schlegel, Finkbeiner & Davis (1998).

### 3.1 Search for cataclysmic variables

So far, there are only three confirmed and one candidate cataclysmic variables known in the whole sample of galactic open clusters: one in M 67 (Gilliland et al. 1991), two in NGC 6791 (Kaluzny & Rucinski 1995) and one in NGC 2158 (Mochejska et al. 2006). All of these clusters are old, and as Melotte 66 is an old and rich cluster we decided to search it for possible cataclysmic variables. Two methods were used.

First, we used the ISIS image subtraction package (Alard & Lupton 1998; Alard 2000) to look for objects showing outbursts. Cataclysmic variables of dwarf nova type have average $M_V = 7.5$ at quiescence with outburst magnitudes spanning the range 2–8 mag (Warner 1995). At the cluster distance, they would be observed at $V \approx 21$ at minimum light and at $13 < V < 19$ at maximum light. With a limiting magnitude of our observations of $V \approx 21$, it should be possible to detect objects of this type while they are in outburst. Our search gave a negative result.

The second method used relies on the fact that cataclysmic variables have blue $U-B$ colours. In Fig. 7, we show a $V(U-B)$ diagram for the cluster field. It contains 10 objects with $U-B < -0.3$. For seven of these objects, we have time series photometry obtained with the FORD2 camera and for two photometry obtained with TEK2 camera. Examination of these light curves showed that none of the objects shows any convincing evidence for variability. The brightest of the blue objects, which we denote as C1, has $V = 18.57$, $B - V = 0.07$ and $U - B = -0.87$. The lack of evidence for variability, including comparison of photometry from 1992 and 1999 seasons, indicates that it is unlikely to be a quasar. It is possible that the star is a hot subdwarf belonging to the cluster. We note that C1 is located very close to the projected cluster centre. Very few confirmed hot subdwarfs are known in open clusters and it is of interest to obtain a spectrum of C1 to clarify its nature. If C1 is a member of the cluster, then its absolute magnitude is $M_V = 5.4$. This value corresponds to the faint end of the absolute magnitude distribution observed for hot subdwarfs in the field and in globular clusters (Moehler et al. 2002, 2004; Lisker et al. 2005).

### 4 ANALYSIS OF THE COLOUR–MAGNITUDE DIAGRAM

Some early photometric studies of Melotte 66 revealed an unexpectedly large widths for the cluster subgiant branch and upper main sequence (Hawarden 1976; Anthony-Twarog et al. 1979). Anthony-Twarog et al. (1994) used $vBvH\beta$ CCD photometry to eliminate differential reddening and variations in cluster metallicity as possible causes of these large widths. They suggested a broad range of rotational velocities among cluster stars as an explanation.
continued until it was impossible to locate pairs with a separation was removed from both corresponding lists. This procedure was from the outer field, a nearest match in the CMD for the inner ring circle and the outer region cover equal areas on the sky. For each star in the outer part of the observed field at $R$ a radius of 21 or 2.8 $\delta V < 200 \pm 21$ or $2.8 < M_V < 7.8$ inside a radius of $R = 550$ arcsec. Note that this is a conservative lower limit because no corrections for the incompleteness of the photometry have been applied. At a radius of 225 arcsec from the cluster centre, the cluster surface density is still a factor of 3 higher than the field star density. In Fig. 9, we show $V/V - I$ CMDs for two groups of stars: those lying inside a radius of $R = 225$ arcsec from the cluster centre and those lying in the outer part of the observed field at $R > 550$ arcsec. The inner circle and the outer region cover equal areas on the sky. For each star from the outer field, a nearest match in the CMD for the inner ring was located. Subsequently, a pair of stars with the lowest separation was removed from both corresponding lists. This procedure was continued until it was impossible to locate pairs with a separation $\delta V < 0.25$ and $\delta(V - I) < 0.15$.

The resulting ‘cleaned’ CMD for the inner region of Melotte 66 is shown in Fig. 10. One may note seven candidate blue stragglers as well as a clump of yellow stragglers at $V \approx 15.4$ and $V - I \approx 0.8$. The occurrence of such objects in the cluster was first noted by Hawarden (1976), and subsequently discussed by other investigators whose papers are quoted above. Fig. 10 shows that the cluster main sequence is very sharply defined on the blue side. In particular, for $17.4 < V < 19.5$ it is possible to distinguish a narrow, well-defined main sequence corresponding to a sample dominated by single stars. Above this sequence is a second sequence consistent with a sample of binary stars with mass ratios close to unity. It merges with the ‘single’ sequence near the turn-off region. As can be seen in Fig. 3, the EC V4, V5, V7 and V9 are located on the binary sequence.

The presence of a well-populated binary sequence in the CMD of Melotte 66 has already been noted by Kassis et al. (1997).

We have estimated the widths of these ‘single’ and ‘binary’ sequences using stars from the cleaned CMD in a rectangle given by $17.5 < V < 19.5$ and $0.7 < V - I < 1.1$. The blue edge of the main sequence in this rectangle was fitted by the second-order polynomial. For each star, we have calculated its distance (in colour) from this polynomial. In Fig. 11, we show a histogram of star counts in bins of 0.015 in $V - I$. Fig. 11 shows two peaks representing the two sequences. A double-Gaussian fit to the two peaks indicates widths of $V - I = 0.042 \pm 0.002$ and $0.048 \pm 0.005$ for the ‘single’ and ‘binary’ sequences, respectively. The two sequences are well resolved in over the range $17.5 < V < 19.5$. At fainter magnitudes, the sequences are smeared by the uncertainties of the colour measurements. At $16.0 < V < 17.5$, the sequences cross each other leading to an apparent broadening of the upper main sequence. Fig. 10 shows that the cluster subgiant branch is well populated, with four or five stars scattered on the blue side. We speculate that these stars represent an extension of the binary sequence in the turn-off region.

We have checked how the $E(B - V)$ extinction varies across the field of the cluster based on the Schlegel et al. (1998) reddening maps. In Fig. 12, we show an $E(B - V)$ differential reddening map with 5 arcmin resolution in a $25 \times 25$ arcmin$^2$ box centred on the cluster. It is clear that even inside the cluster radius $\Delta E(B - V)$ can be as large as 0.09. According to Kassis et al. (1997), Melotte 66 is located about 1.1 kpc below the Galactic disc and 4.4 kpc from the Sun. The line of sight to the cluster does not cross any outer spiral arm of the Milky Way and so the observed gradients of $E(B - V)$ occur in the interstellar matter located between the Sun and the

Figure 8. Star density as a function of radial distance from the centre of Melotte 66.

Figure 9. The CMD’s for the field covering central part of Melotte 66 (left-hand side) and for the ‘outer’ field (right-hand side).

Figure 10. Field-star corrected CMD for the central part of Melotte 66.
clusters, Melotte 66 seems to have a rather high relative frequency of which are probable members of the cluster. Like other old open open cluster Melotte 66. Four out of eight EC are contact systems We have detected a total of 10 photometric variables in the field of the cluster field. The projected stellar density profile was obtained for the cluster field. We show that the angular radius of Melotte 66 reaches at least 550 arcsec. When corrected for the contamination by field stars, the cluster CMD shows a well-defined and narrow main sequence accompanied by a rich sequence of binary stars.

5 CONCLUSIONS

We have detected a total of 10 photometric variables in the field of the old open cluster Melotte 66. Four out of eight EC are contact systems which are probable members of the cluster. Like other old open clusters, Melotte 66 seems to have a rather high relative frequency of contact binaries. Our estimate of the total number of cluster members with $16 < V < 21$ at 1122 stars leads to a relative frequency of EW stars of $0.36 \pm 0.18$ per cent. Note, however, that the sensitivity of our survey for variables is rather low for $V > 20$. This relative frequency can be compared to that observed for field stars in the solar vicinity which is estimated at 0.2 per cent for $3.5 < M_V < 5.5$ and at 0.1 per cent for $M_V = 6.0$ (Rucinski 2006). Three other binaries, including a candidate blue straggler, are detached systems and one is probably a semidetached binary. We also identified a promising candidate for a hot subdwarf cluster member.

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