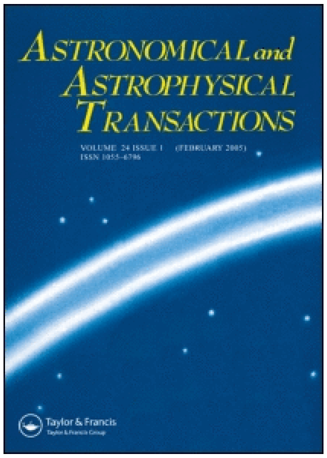

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ON PUTTING THE CATALOGUES OF THE RELATIVE PROPER MOTIONS OF OPEN CLUSTER STARS IN ONE SYSTEM (CLUSTER M67)

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In this paper a method for putting the catalogues of the proper motions of cluster stars in one system is discussed on the base of numerical experiments. The catalogue of proper motions of stars in the field of open cluster M67 based on five catalogues of relative proper motions and the Tycho-2 catalogue is compiled.

Keywords: Open cluster; Proper motion; Membership

1 INTRODUCTION

A great amount of data concerning the determination of proper motions in open cluster (OCl) fields has been published in the literature. The proper motions of some luminous cluster stars can be found in large catalogues of positions and proper motions such as AGK3, PPM or Tycho-2. However, most published determinations of the proper motions of cluster stars are relative as they are evaluated for the estimation of membership probabilities. The random errors in relative proper motions are usually lower than occurring in large catalogues, and the limiting magnitudes are larger too. For example for the well-known old cluster M67 = NGC 2682, one can find determinations of the proper motions in the papers by Sanders (1977), Girard *et al*. (1989), Frolov and Ananyevskaya (1996), Zhao *et al*. (1993), Murray and Clements (1968) and others with limiting magnitude up to $V = 16$. In spite of good accuracy with respect to the random errors of such catalogues, the accuracy of a single catalogue is usually insufficient for investigations of the kinematics of cluster stars, which constrains research in the field of cluster dynamics. An appropriate way to achieve a high-precision catalogue of proper motions is to combine several independent catalogues in one precise catalogue. However, such a combination of catalogues is complicated because of the influence of random errors in the estimates of parameters of the transition equations between the systems of proper motions in various catalogues. Let us consider a variant of the problem when one catalogue is recalculated in the system of another with the help of linear transformation of the form

$$\begin{aligned}\mu_{x1} &= a_1 + b_1\mu_{x1} + c_1\mu_{y1} + m_1V,\\ \mu_{y1} &= a_2 + b_2\mu_{x2} + c_2\mu_{y2} + m_2V,\end{aligned} \qquad (1)$$

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where the last terms in each equation account for the magnitude. We shall not consider the simple method of the use of mean differences between two sets of proper motions because it is not sufficiently accurate (see below).

Let us consider the variables on the right-hand sides of Eq. (1) as factors, and the variables on the left-hand sides as responses as usually accepted in statistics. The elements of the transition matrix and displacement vector of Eq. (1) are usually estimated by the least-squares method. However, in reality, when the values of both the factors and the responses contain random errors, the estimates of parameters in Eq. (1) appear to be biased (Vuchkov *et al.* 1987). Beside this bias one, more effect is manifested. It is well known that random errors widen the distribution of proper motions. This effect leads to the dependence of the value of determinant of the transformation matrix of Eq. (1) on the ratio of dispersions of errors in the left- and right-hand sides of system (1). If this ratio is greater than 1, the determinant turns out to be greater than 1, and vice versa. In the real case this effect is mixed with the effect of real expansion–contraction of the proper motion scale which can exist in particular catalogues. It is precisely the effect of expansion–contraction that causes difficulties for the use of the mean differences method in putting the catalogues of proper motions into one system. The application of system (1) or more complicated nonlinear transformations automatically takes the effect of expansion–contraction into account.

In this paper the efforts to construct a method for compiling a catalogue of proper motions are discussed and illustrated by the case of the open cluster M67.

2 NUMERICAL EXPERIMENTS

To study the influence of random errors on the linking of catalogues of proper motions a set of numerical experiments was performed. The values of components of the three-dimensional radius vectors of star positions in a cluster are set by a random-number generator with the distribution density proportional to e^{-x} with parameters leading to a value of the cluster core diameter of 3 pc. Then for the cluster distance from the Sun (900 pc used for M67) the distances of every model star from the Sun are calculated. The space velocities of cluster stars are taken from the spherically symmetrical normal distribution with dispersion $1.5\,\mathrm{km\,s^{-1}}$. Using the distance of the star from the Sun and the projection of the space velocity generated, the values of the components μ_x and μ_y of proper motion of the star are calculated.

To imitate field stars their distances and space velocities are generated. The linearly increasing function is used as a density distribution of field star distances from the Sun with limiting distance 1500 pc and the dispersion of the spherically symmetrical normal distribution of space velocities is taken to be equal to $30\,\mathrm{km\,s^{-1}}$. The bias of $10\,\mathrm{km\,s^{-1}}$ is added to each value of the space velocity component of the field star to imitate solar space motion. From full space motions the values of proper motion components are calculated. As a last step the normally distributed random errors with various dispersions are added to the proper motions of both field stars and model cluster stars. For each experiment, 500 model cluster stars and 300 field stars are used. The magnitude equation is not determined for any experiment.

Let us discuss the results of the numerical experiments. The parameters of system (1) for the model samples are summarized in Table I, where the estimates of the parameters of Eq. (1) and the determinant of that system together with their rms errors are shown for groups of experiments. The estimates are calculated by the classical least-squares method for various values of error dispersion inserted in model proper motions. Every estimate in the table is derived as the mean value from five experiments executed with individual series of random numbers. All results in this paper are expressed in milliarcseconds per year. In the first two columns of the Table I the dispersions of the errors inserted in model proper motions are shown,

TABLE I The Estimates of Parameters of Transformation Equations for Various Values of Dispersions in Factors and Responses.

S_{resp}	S_{fact}	a_1	b_1	c_1	a_2	b_2	c_2	*Determinant*
0	1	0.150 ± 0.032	0.962 ± 0.004	−0.002 ± 0.003	0.101 ± 0.006	0.005 ± 0.003	0.970 ± 0.003	0.933 ± 0.006
0	2	0.384 ± 0.032	0.885 ± 0.007	0.012 ± 0.005	0.428 ± 0.066	0.007 ± 0.005	0.883 ± 0.014	0.781 ± 0.016
0	3	0.812 ± 0.079	0.765 ± 0.016	0.022 ± 0.010	0.833 ± 0.108	0.015 ± 0.009	0.763 ± 0.026	0.585 ± 0.030
0	4	1.305 ± 0.103	0.643 ± 0.023	0.011 ± 0.011	1.241 ± 0.096	0.019 ± 0.009	0.666 ± 0.029	0.429 ± 0.014
0	5	1.650 ± 0.106	0.548 ± 0.023	0.015 ± 0.013	1.725 ± 0.120	0.025 ± 0.012	0.565 ± 0.036	0.311 ± 0.030
0	6	2.109 ± 0.126	0.456 ± 0.022	0.014 ± 0.016	1.952 ± 0.174	0.026 ± 0.010	0.477 ± 0.012	0.219 ± 0.024
0	7	2.417 ± 0.109	0.375 ± 0.023	0.019 ± 0.010	2.201 ± 0.149	0.031 ± 0.009	0.405 ± 0.033	0.153 ± 0.021
6	2	0.424 ± 0.087	0.854 ± 0.010	0.008 ± 0.007	0.669 ± 0.061	−0.016 ± 0.020	0.855 ± 0.023	0.730 ± 0.012
2	6	2.167 ± 0.158	0.452 ± 0.025	0.010 ± 0.016	1.999 ± 0.160	0.024 ± 0.009	0.469 ± 0.033	0.214 ± 0.025
5	3	0.911 ± 0.171	0.767 ± 0.019	0.020 ± 0.028	0.717 ± 0.117	−0.001 ± 0.014	0.764 ± 0.024	0.587 ± 0.031
3	5	1.700 ± 0.158	0.555 ± 0.024	0.002 ± 0.019	1.738 ± 0.134	0.018 ± 0.021	0.581 ± 0.040	0.323 ± 0.033
4	7	2.507 ± 0.149	0.380 ± 0.023	0.010 ± 0.008	2.264 ± 0.141	0.022 ± 0.012	0.397 ± 0.036	0.153 ± 0.022
7	4	1.132 ± 0.155	0.659 ± 0.032	−0.003 ± 0.015	1.547 ± 0.167	−0.019 ± 0.019	0.645 ± 0.043	0.429 ± 0.047
1	0	−0.024 ± 0.033	1.004 ± 0.004	0.002 ± 0.002	0.015 ± 0.015	−0.003 ± 0.004	1.000 ± 0.002	1.005 ± 0.005
2	0	0.069 ± 0.048	0.993 ± 0.006	−0.004 ± 0.007	0.008 ± 0.052	0.002 ± 0.003	0.998 ± 0.004	0.992 ± 0.006
3	0	0.082 ± 0.087	1.003 ± 0.011	−0.016 ± 0.010	−0.015 ± 0.056	−0.006 ± 0.008	1.022 ± 0.009	1.025 ± 0.017
4	0	0.084 ± 0.087	0.995 ± 0.015	0.005 ± 0.011	0.104 ± 0.066	−0.011 ± 0.009	0.983 ± 0.019	0.980 ± 0.034
5	0	−0.004 ± 0.100	0.995 ± 0.012	0.003 ± 0.019	−0.103 ± 0.050	−0.013 ± 0.010	0.996 ± 0.010	0.991 ± 0.014
6	0	0.017 ± 0.099	0.970 ± 0.020	0.001 ± 0.009	0.203 ± 0.090	−0.025 ± 0.021	0.983 ± 0.010	0.953 ± 0.016
7	0	−0.168 ± 0.203	1.003 ± 0.018	−0.002 ± 0.020	0.310 ± 0.217	−0.030 ± 0.017	0.969 ± 0.029	0.973 ± 0.045

for responses in the first column, and for factors in the second column. The rest of the columns contain least-squares estimates of the coefficients of system (1) with their rms errors for five experiments each; in the last column the value of the determinant of system (1) with its rms error may be seen. Remember that, when the errors on both the left- and right-hand sides of Eq. (1) equal to zero the values of a_1, a_2, c_1 and b_2 equal zero but $b_1 = c_2 = 1$.

The values from Table I show that some bias in the displacement vector (a_1, a_2) appears even for small errors of proper motions although this bias is not very large even for large errors. For zero errors in factors the bias is statistically insignificant as one would expect for the classical least-squares method. The value of the determinant of the transformation matrix in Eq. (1) appears to be heavily dependent on the error dispersions in the factors, but for zero dispersion of errors in factors the determinant statistically insignificantly differs from zero, even for large errors in the responses. For convenience the results of the experiments are shown in Figures 1 and 2. Figure 1 shows the dependence of the bias in the displacement vector components on the error dispersions in the factors. In the figure the full symbols refer to a_1 values, and the open symbols to a_2; the circles show the case when $S_{\mathrm{resp}} = 0$, and the triangles when $S_{\mathrm{resp}} > 0$. Figure 2 shows the dependence of the determinant of the transformation matrix on the error dispersions in the factors. The designations here are the same as in Figure 1. One can see that fictitious contraction–expansion of the system of proper motion is appreciable even for small errors in the factors. For example, the proper motions in the AGK3 catalogue must be on average five times the real proper motions. It is worth noting that the fact that the value of the determinant is independent of the errors in the responses (see Table I) means that application of system (1) leads to correction of the effect of widening of proper motion distributions caused by random errors. Another consequence is that one must use the catalogue with the smallest random errors in proper motions to minimize contraction–expansion in the resulting catalogue.

Discussion of the results of numerical experiments leads to the following method of combining the proper motion catalogues. In the first step, one catalogue which covers most of the area of the sky must be chosen as the leading catalogue. It is convenient to choose Tycho-2 as this catalogue in order to obtain a combined catalogue in an absolute system. Then the next catalogue that contains the largest number of common stars with the first catalogue must be chosen. It must be transformed into the system of the leading catalogue by determination of the coefficients of transformation (1) and the necessity for introducing a correction in the values (a_1, a_2) must be checked by calculating the mean differences between proper motions of two catalogues. Then the proper motions of two catalogues have to be averaged. The catalogue derived in this manner can be combined with the third catalogue and so on.

The preliminary catalogue derived can be utilized to determine the magnitude equation. Although cluster members share the same proper motion of the cluster, one can use them to

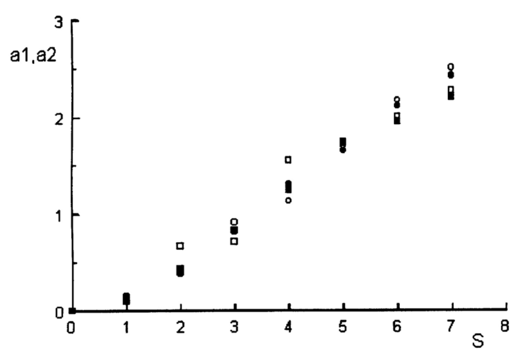

FIGURE 1 Dependence of the bias in the displacement vector components on the error dispersions in the factors.

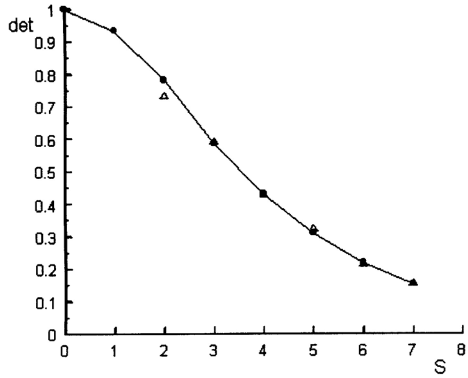

FIGURE 2 Dependence of the determinant of the transformation matrix on the error dispersions in the factors.

derive the magnitude dependence of the proper motions and probable cluster members can be selected with the help of photometric diagrams. The evaluation of the magnitude equation in the preliminary catalogue provides the opportunity for determining the magnitude equation for every original catalogue separately during the fulfilment of the subsequent steps.

In order to construct the final catalogue, one has to transform each original catalogue into the system of preliminary catalogue. For each catalogue the coefficients of system (1) including the magnitude term must be evaluated and also the dispersion of the deviations in the equations of condition. This dispersion can be used in the procedure for averaging proper motions from the catalogues to estimate the weights of the original catalogues.

3 PROPER MOTIONS IN THE FIELD OF M67

Let us consider the usage of the proposed method for the case of the well-studied old open cluster M67 = NGC 2682. To evaluate the mean proper motions in the cluster field the catalogues mentioned above are used. According to the procedure discussed above, the preliminary catalogue is formed, and as the first catalogue that by Frolov and Ananyevskaya (1996) is used. The preliminary catalogue is transformed into the system of the Tycho-2 catalogue. Figures 3 and 4 show the magnitude equations for the proper motions of preliminary catalogue in the right

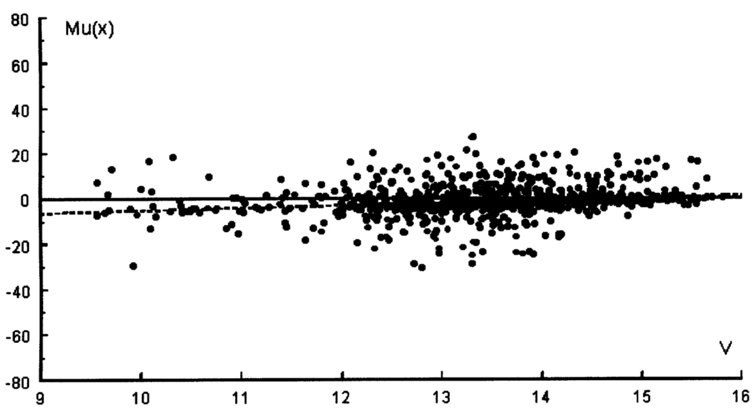

FIGURE 3 Magnitude equation for the proper motions of the preliminary catalogue in the right ascension.

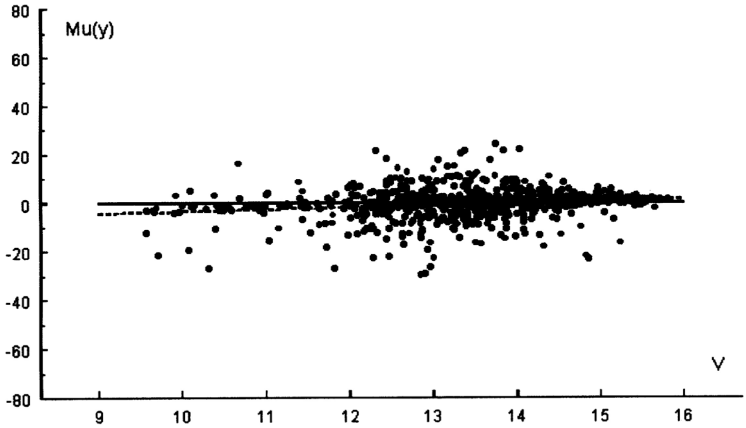

FIGURE 4 Magnitude equation for the proper motions of the preliminary catalogue in the declination.

ascension and declination respectively. Probable cluster members for this goal are extracted from the sample with the use of photometric criteria. In both coordinates the magnitude equations appear to be linear and appropriate corrections are inserted in the values of the proper motions of preliminary catalogue. The linear dependences of proper motion components on stellar magnitude are shown in the figures by dashed curves. Table II shows the coefficients of the transformation Eq. (1) for each original catalogue transformation in the system of preliminary catalogue with their rms errors.

In Table III the estimates of the coefficients of the magnitude equation with their rms errors and dispersions of rms deviations in the equations of the conditions are shown. The latter values are used for evaluating the weights of original catalogues for estimating the mean proper motions.

Some comments must be made on the contents of these tables. We do not include the values of the determinants of transformation matrices in the tables because it is impossible to separate the effects of expansion–contraction of the systems of proper motion and the widening

TABLE II Coefficients of the Transformation Formulae.

Catalogue	a_1	a_2	b_1	b_2	c_1	c_2
Frolov and Ananievskaya (1996)	8.72 (1.20)	−1.52 (1.76)	0.95 (0.01)	0.00 (0.01)	0.01 (0.01)	0.92 (0.01)
Zhao *et al.* (1993)	3.51 (0.94)	−11.69 (0.82)	0.92 (0.01)	0.04 (0.01)	0.03 (0.01)	0.90 (0.01)
Girard *et al.* (1989)	−7.45 (0.48)	−0.40 (0.98)	0.96 (0.02)	0.03 (0.01)	−0.00 (0.01)	1.00 (0.01)
Murray and Clements (1968)	−17.59 (1.95)	−18.38 (1.90)	0.85 (0.02)	0.01 (0.02)	−0.06 (0.02)	0.79 (0.02)
Sanders (1989)	−7.33 (0.10)	−4.43 (0.67)	0.45 (0.08)	−0.12 (0.04)	−0.20 (0.11)	0.20 (0.06)

TABLE III Magnitude Equations and Dispersions.

Catalogue	m_1	m_2	s_1	s_2
Frolov and Ananievskaya (1996)	−1.01 (0.09)	−0.18 (0.14)	3.54	5.20
Zhao *et al.* (1993)	−0.77 (0.07)	0.61 (0.06)	2.92	2.54
Girard *et al.* (1989)	–	−0.25 (0.07)	1.93	1.87
Murray and Clements (1968)	0.64 (0.15)	1.08 (0.14)	3.41	3.33
Sanders (1989)	–	−0.26 (0.05)	2.17	1.23
Tycho-2	–	–	2.10	2.12

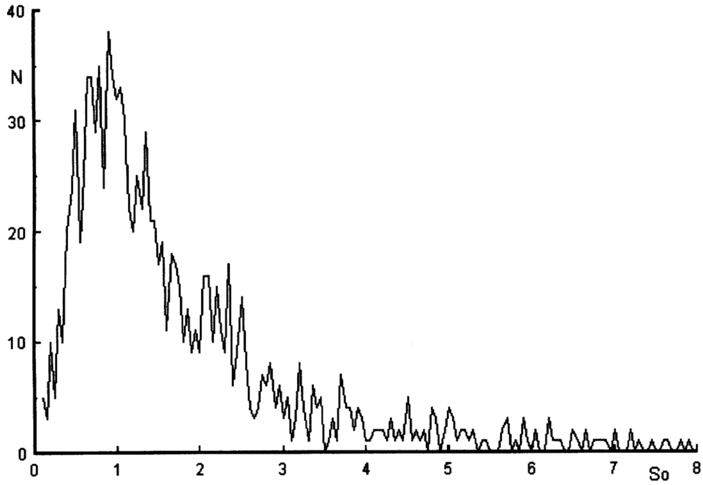

FIGURE 5 Frequency distribution of the errors of the total proper motions of the final combined catalogue.

of proper motion distributions due to random errors. Only for the catalogue by Murray and Clements (1968) (the value of determinant equals 0.66) does this value significantly differ from zero, but this case emphasizes that the mean differences are insufficient for combining catalogues. The case of the catalogue by Sanders (1977) is specific. In the basic work by Sanders (1977) the coordinates of stars are not given, which forced us to use the catalogue of proper motions of probable members (Sanders 1989). The considerable constriction in the spread of the sample (absence of most field stars) leads to lower reliability of the estimates of transformation parameters. For this catalogue we used twice the lower weight. In Table III the absence of a value means that this coefficient appears to be statistically insignificant; this term is rejected from regression model and the solution of a system repeated without a magnitude term. It ought to be mentioned that for the M67 field in the Tycho-2 catalogue the magnitude term insignificantly differs from zero.

Figure 5 shows the frequency distribution of the errors of total proper motions of the final combined catalogue calculated as $s_0 = (s_\alpha^2 + s_\delta^2)^{1/2}$, where s_α and s_δ are rms errors of the weighted mean components of proper motions from final catalogue. One can see from the figure that most of the stars of final catalogue have rms errors of components of proper motion less than $0.001''$ year^{-1}.

4 DISCUSSION

The method proposed is used to compile the catalogue of mean proper motions of 1141 stars in the field of the open cluster M67. Stars which are taken from two or more catalogues are left in the list to minimize the errors of identification. Using the Sanders (1971) method, 520 probable cluster members are selected from the whole list. This number corresponds to a membership probability of 68%. The frequency distribution of estimates of membership probabilities for stars in the catalogue is shown in Figure 6 which confirm the high quality of the mean proper motions of most stars in the catalogue. One can see that, in spite of the fact that the proper motions in the catalogue do not have equal accuracies, the separation between members and non-members is very reliable, although some field stars remain in the sample of members. The components of the proper motion of a cluster as a whole derived by the Sanders method are

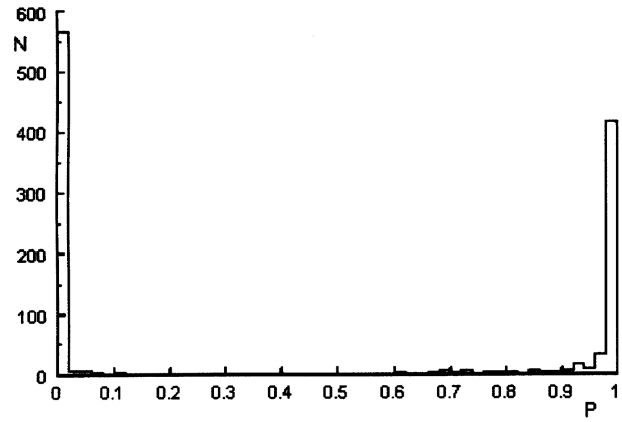

FIGURE 6 Frequency distribution of estimates of membership probabilities for stars in the catalogue.

equal to $\mu_\alpha = -7.62 \times 10^{-3''}$ year^{-1} and $\mu_\delta = -3.94 \times 10^{-3''}$ year^{-1} with the rms error of the order of $0.04 \times 10^{-3''}$ year^{-1}, which correspond to an error in the components of the space velocity of 0.2 km s^{-1}. The dispersion of proper motions of cluster members (the parameter of the Sanders formulae) is equal to $0.91 \times 10^{-3''}$ year^{-1} or 3.9 km s^{-1}.

For convenience the photometric values in the ultraviolet (UBV) system are included in the catalogue. These data are chosen from papers by Sanders (1989) and Montgomery *et al.* (1993). In some cases when no photoelectric or change-compiled device measurements have been made on the star, the photographic values from Murrey and Clements (1968) are taken. The colour–magnitude diagram for stars with membership probabilities of 90% or higher is shown on Figure 7. This diagram shows that a considerable portion of non-members remains in the sample. This may be interpreted as some the fact that the Sanders method does not provide a sufficiently high accuracy of the input catalogue because no rigorous approximation of the proper motion distribution of field stars is available.

The catalogue of proper motions in the field of cluster M67 can be requested from the author (email: Alexhander.Loktin@usu.ru.)

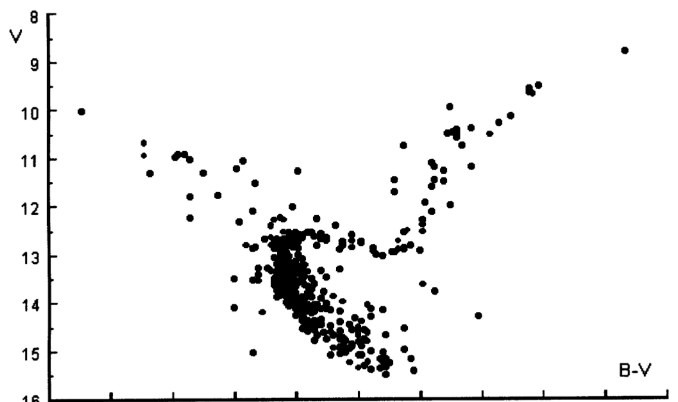

FIGURE 7 Colour–magnitude diagram for stars with membership probabilities of 90% or higher.

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