

# Catalogue of variable stars in open cluster fields<sup>★</sup>

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Received 7 March 2012 / Accepted 4 October 2012

## ABSTRACT

**Context.** We present the first catalogue of known variable stars in open cluster regions and with up to two times the given cluster radius. This gives basic information about the distribution of variable stars in cluster fields for the complete sky.

**Aims.** Knowledge of the variable star contents in open clusters is a significant advantage in their study. Analysing variability of cluster members and fields stars also allows us to study the characteristics of stars and clusters together. This catalogue of variable stars in open cluster fields is the first step in supporting such studies.

**Methods.** We took all variable and suspected variable stars into account from the most complete collection, “The AAVSO Variable Star Index”, and did a cross-match of these stars with the most complete catalogue of galactic open clusters named DAML02.

**Results.** Our on-line catalogue presently contains 18 065 variable stars. We present the basic statistical distribution according to types of variability.

**Key words.** open clusters and associations: general – catalogs – stars: variables: general – proper motions

## 1. Introduction

The study of an individual star provides only limited, frequently inaccurate and uncertain information about it and possibly about the interstellar medium between this object and us. On the other hand, open clusters provide an ideal opportunity to simultaneously study a group of stars located in a relatively small space, at the same distance from the Sun, and with the same age and initial chemical composition. The detection of any variable star in such stellar aggregates and its usage for further information mining make research of open clusters very effective. For example, when observing stellar clusters containing variable stars, it is possible to obtain data of the characteristics of variable stars, as well as of whole open clusters (Joshi et al. 2012). This improves our knowledge about both variable stars and open clusters and yields new data for the study of the dynamics, evolution, and structure of the whole Galaxy. This idea is partly valid even in the case that an individual star, the aim of a study, is only located in an open cluster field. In time of CCDs, it is clear that an observer simultaneously obtains photometric data about all stars in the corresponding frame. Thus, such observations of a star only located in an open cluster field, without a confirmed membership in it, can help study the open cluster itself as well. We are certain that in this context, it is important to have a catalogue of variable stars in open cluster fields.

A similar project for Galactic globular clusters was initiated by Clement et al. (2001) on the basis of the first corresponding catalogue by Sawyer (1939). For globular clusters, the task of

compiling a list of variable members is rather straightforward because there is almost no contamination of fore- and background objects in the cluster areas.

At present, about 2100 open clusters or candidates of clusters are known in the Galaxy (DAML02 Catalogue, Version 3.2<sup>1</sup> Dias et al. 2002a) and this is probably only a low percentage of their total population. Most open clusters are too far away and therefore too faint to be observable. Furthermore, a substantial portion of open clusters is hidden behind interstellar material in the Galaxy plane (Froeblich et al. 2007). From an evolutionary point of view it is obvious that we are currently only aware of a small portion of all clusters that have ever existed in our Galaxy. As they drift along their orbits during their lives, some cluster members escape the hosting cluster thanks to velocity changes in mutual close encounters (whole clusters or their members), tidal forces in the galactic gravitational field, and encounters with field stars and interstellar clouds crossing their way. A typical open cluster has lost most of its member stars after several hundred Myrs (de la Fuente Marcos & de la Fuente Marcos 2010). Only some of them reach an age older than a few billion years. The escaped individual stars continue to orbit the Galaxy on their own as field stars. This has given rise to the popular view that most or even all field stars in our Galaxy as well as other galaxies have their origin in clusters. Thus, the importance of open cluster research is crucial.

Although it seems that the frequency of open cluster studies is increasing, many clusters remain unstudied, and most important questions still don't have definitive answers. So far, there are limited surveys like the WIYN Open Cluster Study, which investigates 14 northern clusters (Geller & Mathieu 2012),

<sup>★</sup> The current version of the catalogue is only available at the CDS via anonymous ftp to cdsarc.u-strasbg.fr (130.79.128.5) or via <http://cdsarc.u-strasbg.fr/viz-bin/qcat?J/A+A/548/A97>

<sup>1</sup> <http://www.astro.iag.usp.br/~wilton/>

or the Southern Open Cluster Study (SOCS), which includes 24 southern open clusters (Kinemuchi et al. 2010). There are also several individual studies, such as De Marchi et al. (2010), Twarog et al. (2011), or Paunzen et al. (2010). The most complete database of data devoted to open clusters is WEBDA<sup>2</sup>. It includes astrometric data in the form of coordinates, rectangular positions, proper motions, photometric measurements, and spectroscopic data, such as spectral classification, radial velocities, and rotational velocities. In addition, it contains miscellaneous types of other data such as membership probabilities, orbital elements of spectroscopic binaries, and periods of variability for different kinds of variable stars, including a whole set of bibliographic references. At present, WEBDA includes information about 1100 open clusters in our Galaxy and in the Small Magellanic Cloud.

Currently, the presentation of the variable star content within WEBDA is somewhat inhomogeneous. The corresponding data will only be included in the database if authors of the relevant papers explicitly state that an object is in an open cluster field.

The relevant data can be found within WEBDA in the following types:

- FRQ: collection of multiple frequencies for photometrically variable stars such as  $\delta$  Scuti,  $\beta$  Cephei,  $\gamma$  Doradus, and slowly pulsating B stars;
- IDS: the cross-identifications with double and multiple star components from the Washington Index of double stars (Hartkopf & Mason 2005);
- ORB: orbital elements for spectroscopic binaries;
- PRD: collection of periods for photometrically variable stars such as eclipsing binaries, contact binaries, variable stars by rotational modulation,  $\delta$  Scuti type pulsators;
- SB: numbers of known spectroscopic binaries in each cluster.

The individual variables are separately listed on each cluster page in the file type “Notes”. The latest edition of the General Catalog of Variable Stars (hereafter GCVS) is also incorporated in the data base and can be fully queried.

However, no complete study exists that shows the distribution of different kinds of variable stars in open clusters. There are only catalogues of eclipsing or spectroscopic binaries in open clusters in Popova & Kraicheva (1984) and Clausen & Giménez (1987). In addition there are studies of variable stars in individual open clusters (e.g. Xin et al. 2002). We compiled the first comprehensive list of variable stars in open clusters and their close vicinity.

## 2. Description of the catalogue

The latest version of the GCVS contains 45 835 records (Samus et al. 2012). The New Catalogue of Suspected Variable Stars and its Supplement<sup>3</sup> (Kukarkin et al. 1982; Kazarovets et al. 1998) contain 14 811 and 11 206 stars, respectively. However, the number of known variable stars is several times higher. At present, the most complete database of variable stars is managed by the American Association of Variable Star Observers, AAVSO, as the International Variable Star Index (VSX). It is available on-line at <http://www.aavso.org/vsx> or at the Strasbourg astronomical Data Centre (Watson et al. 2012). We used the version available at the CDS on April 29, 2012, containing 209 285 records (including 575 duplicities). Using the list of stars included in the VSX and the version 3.2. Catalogue

<sup>2</sup> <http://webda.physics.muni.cz> (Mermilliod & Paunzen 2003)

<sup>3</sup> <http://www.sai.msu.su/gcvs/gcvs/nsv/>

of Open Clusters DAML02<sup>4</sup> (Dias et al. 2002a), we did a match between the two sources of data. We divided the open clusters into two categories according to their sizes, where the limiting diameter was 60'. We restricted our sample to clusters with diameters of less than five degrees, with the exception of the Hyades (Melotte 25). The discarded clusters are Collinder 173, Collinder 285, Collinder 302, Platais 2, Platais 8, Platais 9, and Platais 10. For both samples of open clusters, we generated a list of all suspected variables and variable stars located within the fields of open clusters. We checked the cluster fields and vicinities up to two times the given cluster radius. In the first group of 461 open clusters smaller than 60', we found 8 938 variable stars. In the second group of 74 open clusters, we located 9 127 variable objects. An important concern is proper motion data. We matched all variable stars of our two samples against the PPMXL catalogue of positions and proper motions within the ICRS (Röser et al. 2010). We determined new mean cluster parameters (see Sect. 2.1). In addition, we used the values from the DAML02 catalogue.

The database of variable stars in both groups of open clusters (Table 1) is available on-line at the CDS and has following structure:

- VSNo – Number of star, the prefixes “S” or “L” respectively mean the star belongs to an open cluster smaller or larger than 60';
- Name – Name of variable star;
- PPMXL – Identifier of star in PPMXL catalogue;
- RAVS – Right ascension J2000.0 (epoch 2000.0) of variable star in degrees;
- DEVS – Declination J2000.0 (epoch 2000.0) of variable star in degrees;
- VSpmRA – Proper motion of variable star in RA\*cos(DE) [mas/yr];
- VSpmDE – Proper motion of variable star in Declination [mas/yr];
- VSpmRA\_e – Mean error of variable star proper motion in VSpmRA\*cos(DE) [mas/yr];
- VSpmDE\_e – Mean error of variable star proper motion in DE [mas/yr];
- Nomeas – Number of measurements used to derive mean proper motion;
- Flag1 – Taken from Röser et al. (2010), where one can find more details. It is a bitwise or number ( $\Sigma^i$ ), where each bit number (i) has the meaning:
  - #0 (1) = If set, one of the coordinates has an excessively large chi square;
  - #1 (2) = Row is from PPMXL Röser et al. (2008). These objects are mostly Tycho stars that were masked out of USNO-B.
  - #2 (4) = Row is from PPMXL Röser et al. (2008) and replaces a single row from USNO-B. This is done when the astrometry from PPMXL was better (in terms of error estimates) than the astrometry of the corresponding PPMXL object.
  - #3 (8) = Row replaces multiple USNO-B1.0 objects. When PPMXL contains an object that has more than one counterpart in USNO-B1.0, all such counterparts are discarded on the assumption that they should have been matched in USNO-B1.0 or result from erroneous matches. For these rows, bit#1 is always 1.
- Type – type of variability, see <http://www.aavso.org/vsx/index.php>

<sup>4</sup> <http://www.astro.iag.usp.br/~wilton/>

[view=about.vartypes](#) or <http://www.aavso.org/vsx/help/VariableStarTypeDesignationsInVSX.pdf> for details;

- Max\_l – Limit; flag on magnitude in maximum of brightness;
- Max – Magnitude at maximum, or amplitude of light changes;
- Max\_u – Uncertainty flag on maximum of brightness;
- Max\_p – Passband on maximal magnitude;
- Min\_a – Flag “(” indicates an amplitude given in next column;
- Min\_l – Limit flag on magnitude in minimum of brightness;
- Min – Magnitude at minimum, or amplitude of light changes;
- Min\_u – Uncertainty flag on minimum of brightness;
- Min\_p – Passband on minimal magnitude;
- Epoch – Epoch of maximum or minimum (HJD);
- Epoch\_u – Uncertainty flag (:) on epoch;
- Period\_l – Limit flag on period. If the period is lower or higher than limit, then value is preceded by “>” or “<”. “(” indicates that the period is the mean cycle time of a U Gem or recurrent nova;
- Period – Period of the variable in days;
- Period\_u – Uncertainty or note flag on Period (“:” uncertainty flag, “)”) value of the mean cycle for U Gem or recurrent nova, “\*N” the real period is likely a multiple of the quoted period, “/N” the period quoted is likely a multiple of the real period;
- DVSm – Distance to the centre of open cluster in arcmin;
- DVSp – Distance to the centre of open cluster in percent of open cluster apparent radius  $Diam/2$ ;
- OCL – Name of open cluster (OC);
- RAOC – Right ascension (J2000.0) of OC centre;
- DEOC – Declination (J2000.0) of OC centre;
- Flag2 – Note to open cluster:
  - *e* embedded open cluster (or cluster associated with nebulosity);
  - *g* possible globular cluster;
  - *m* possible moving group
  - *n* “non-existent NGC” (RNGC, Sulentic & Tift 1979). Some of Bica’s POGRs are also “non-existent NGC” objects;
  - *o* possible OB association (or detached part of);
  - *p* POGR (possible open cluster remnant) – Bica et al. (2001);
  - *v* clusters with variable extinction (Ahumada et al. 2001);
  - *r* recovered: “non-existent NGC” that are very visible in the DSS image inspection;
  - *d* dubious: objects considered doubtful by the DSS image inspection;
  - *nf* not found: objects not found in the DSS image inspection (wrong coordinates?);
  - *cr* cluster remnant (Pavani & Bica 2007);
  - *OC?* possible cluster (Kronberger M., priv. comm.);
  - *OC* likely cluster (Kronberger M., priv. comm.);
  - *IR* discovered in infra-red but are visible in the DSS images inspection.
- Diam – Apparent diameter of open cluster in arcmin;
- *d* – Distance of open cluster [pc];
- $E(B - V)$  – reddening, colour excess in  $(B - V)$  [mag];
- $\log t$  – logarithm of the age of open cluster in years;
- Nc – estimated number of members in the open cluster;
- OCpmRA – mean cluster proper motion in RA [mas/yr];
- OCpmRA\_e – error of mean cluster proper motion in  $\mu_\alpha \cos \delta$ , ICRS [mas/yr];

- OCpmDE – proper motion in  $\mu_\delta$ , ICRS [mas/yr];
- OCpmDE\_e – error of proper motion in DE [mas/yr];
- Npm – number of stars used to derive mean cluster proper motion;
- Ref1 – reference to proper motion – Z – this paper, Table 2; D – see Dias et al. (2002a) for details;
- RV – mean cluster radial velocity [km s<sup>-1</sup>];
- eRV – error of radial velocity [km s<sup>-1</sup>];
- Nrv – number of stars used to derive mean cluster radial velocity;
- Ref2 – reference to radial velocity – see Dias et al. (2002a) for details;
- ME – mean cluster metallicity;
- eME – error of cluster metallicity;
- Nme – number of stars used to determine mean cluster metallicity;
- TrTyp – Trumpler classification of open cluster.

The number of variable stars is increasing rapidly. The catalogue given in Table 1 is only the starting version of such a catalogue, which should be updated. We are going to publish updates irregularly when the number of newly added variable stars in VSX reaches 15 000.

### 2.1. Mean proper motions of open clusters

A homogeneous data set of mean cluster proper motions has not been available until now. We therefore used the following sources (sorted alphabetically) to compile a new catalogue:

- Baumgardt et al. (2000): based on the HIPPARCOS catalogue (Perryman & ESA 1997);
- Beshenov & Loktin (2004): based on the Tycho-2 catalogue (Høg et al. 2000);
- Dias et al. (2001, 2002b): based on the Tycho-2 catalogue;
- Dias et al. (2006): based on the UCAC2 catalog (Zacharias et al. 2004);
- Frinchaboy & Majewski (2008): based on the Tycho-2 catalogue;
- Kharchenko et al. (2005): based on the ASCC2.5 catalogue (Kharchenko 2001);
- Krone-Martins et al. (2010): based on the Bordeaux PM2000 proper motion catalogue (Ducourant et al. 2006);
- Robichon et al. (1999): based on the HIPPARCOS catalogue;
- van Leeuwen (2009): based on the new HIPPARCOS catalogue.

If more than one measurement is available, a weighted mean was calculated, using the reciprocal errors listed in the individual source as weights. Outliers were identified when more than two values were available. Only seven outliers were found in the complete sample: Harvard 76, IC 4665, Melotte 111, NGC 7092, Pismis 28 and Ruprecht 9 (Dias et al. 2006), NGC 6250 (Frinchaboy & Majewski 2008), as well as Melotte 20 (Dias et al. 2001). Those data points were not included in the final compilation.

In total, a catalogue of proper motions for 879 open clusters was compiled, from which 436 have more than one available measurement. Table 2 lists the catalogue.

## 3. Results, statistics

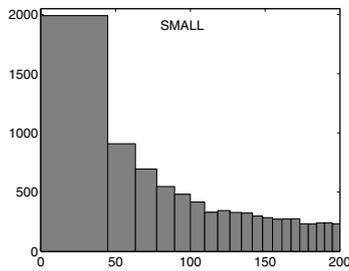
### 3.1. Membership

A detailed membership analysis of the catalogue stars to the corresponding cluster is beyond the scope of this paper. However,

**Table 2.** New compilation of proper motions for 721 open clusters ( $\mu_{\alpha^*} = \mu_{\alpha} \cos \delta$ ).

Cluster	$\mu_{\alpha^*}$	$\sigma(\mu_{\alpha^*})$	$\mu_{\delta}$	$\sigma(\mu_{\delta})$	$N$
Alessi 1	+6.5	0.4	-7.7	0.3	1
Alessi 2	-0.1	0.4	+0.3	0.5	1
Alessi 3	-11.6	0.4	+12.6	0.5	1
Alessi 5	-9.9	0.3	+3.6	0.4	2
Alessi 6	-6.0	0.4	-5.7	0.4	2
Alessi 8	-5.3	0.3	-5.4	0.3	2
Alessi 9	+11.6	0.3	-9.7	0.3	1
Alessi 10	+1.3	0.4	-8.6	0.3	2
Alessi 12	+1.5	0.1	-4.0	0.2	2
Alessi 13	+37.0	0.7	-3.2	0.4	1
Alessi 19	-0.5	0.2	-7.0	0.4	1
Alessi 20	+7.5	0.4	-2.6	0.5	1
Alessi 21	-3.7	0.4	+3.0	0.4	1

**Notes.** The complete table is only available at the CDS.

**Fig. 1.** Distribution of variable stars according to the distance to the cluster centre in units of the corresponding radius for open clusters of diameters smaller than  $60'$ .

as a first heuristic approximation, we present the dependence of areal density of variable stars on the distance to the published cluster centres. The distances are expressed in units of the given accepted cluster radii. We want to emphasise that, although several improvements have been made over the last decades, most of the centre coordinates and angular radii still arise from the visual inspection of photographic plates.

Figure 1 shows the “distance distributions” only for studied open clusters smaller than  $60'$ . We constructed a system of concentric circles around the centre of each open cluster with the same area. Thus we can really study the areal density of variable stars in increasing distant from the open cluster centre. In this figure and Fig. 3 columns with decreasing widths correspond to a decreasing thickness of those concentric circles. We learned that variable stars found in the area of open clusters larger than  $60'$  (mostly nearby clusters) are strongly dominated by variables behind them. However, a detailed kinematic study of the objects might overcome this problem because these clusters should have significant proper motions, while background objects have none. The large all-sky-catalogues, like the PPMXL (Röser et al. 2010), still lack the accuracy needed to perform such analysis.

For the smaller clusters we can assume that stars closer than 50% to the centre of the cluster are most probably members of the cluster according to the typical shape of cluster density profiles (Seleznev et al. 2010). In general, the radial density for the members of open clusters can be well fitted by a King profile. Sanchez & Alfaro (2009) present the internal spatial structure of 16 open clusters on the basis of positional, as well as kinematic data. Figure 2 (left panel) shows the distribution of members for the distant open cluster NGC 2194, which has a diameter of  $9'$ . Concentration of the members to the centre is clearly visible,

supporting our consideration. About 60% of our corresponding objects fall within this range. Going further out from the centre, the density of variable stars drops to the density of the field variable stars.

### 3.2. Type of variability

There are about almost one hundred different classes and subclasses of variability given in the GCVS. However, new types and new divisions of variable stars still appear. The new structure was proposed at the 26th General Assembly of the IAU (Samus 2006)<sup>5</sup>, but it has not been accepted so far. The Variable Star Index of the AAVSO very often uses “new definitions” of variability types taken from original papers, especially when describing results of a survey. In this paper we used types of variability from AAVSO VSX<sup>6</sup> However, we used the original GCVS division in the following categories of variable stars: eruptive, pulsating, rotating, cataclysmic variables, eclipsing binary systems, intense variable X-ray sources, and others. The group of new variability types was dissolved into the previous seven groups according to the main characteristics of the objects according to variable star designation in VSX. Objects with unknown kinds of variability are marked as “-”, “\*”, VAR, or MISC with no information about variability were counted into the group “Others”. Unclear classification of variability shown by a sign “:” is counted in the corresponding group and separately as an unclear member of this group. When the classification contains two or more types with a logical “or” (sign “|”), the classification is uncertain and all possible types are indicated. If these types belong to one class of variability we count the star once in that type of variability. If classified types differ we count them separately as unclear determination in corresponding groups of variability. When a star shows two types of variability which is demonstrated by a logical “and” (sign “+”), we count the star in each of the groups of variable stars. That certainly means that the total sum of stars in all groups is larger than the number of stars in the catalogue. The obtained distribution of the main types of variable stars in both catalogues (VSX and GCVS) and for both smaller and larger open clusters are given in Tables 3 and 4 and shown in Fig. 2. The given variable star-type distribution provides us only a raw image of the real situation. Here, the compared GCVS sample is the electronic edition of March 2012 at the CDS (Samus et al. 2012), which contains 45 835 variable stars. The used AAVSO Variable Star Index<sup>7</sup> is the public version available at CDS on April 29, 2012 containing 209 285 objects (Watson et al. 2012). The number of unveiled variable stars is growing, and the classification of variability type is improving, but unfortunately the processing is not going evenly. The sky coverage is then not proportioned well.

After inspecting Fig. 3 we conclude that the four most numerous groups of variable stars in open clusters all display an apparent concentration around the centre of small clusters. However, the affinity is different. Ignoring the most numerous group of yet unconfirmed or unspecified variables, the most common types of variables found in the area within two radii from the centres of open clusters are eruptive and pulsating variables (see Table 4). They have quite a disjuncted distribution function: while the prevailing majority of eruptive variables is

<sup>5</sup> <http://www.sai.msu.su/gcvs/future/classif.htm>

<sup>6</sup> See details in help at <http://www.aavso.org/vsx/help/VariableStarTypeDesignationsInVSX.pdf> and GCVS (Samus et al. 2012).

<sup>7</sup> <http://www.aavso.org/vsx>

**Table 3.** Numbers of different type variable stars in open clusters smaller and larger than 60'.

Type	Smaller			Larger			Total
Eruptive	1982	167	0	749	83	0	2981
Pulsating	1819	303	90	3112	539	209	6072
Rotating	1018	118	3	793	61	12	2005
Cataclysmic	41	11	0	68	11	1	132
Eclipsing	1162	110	42	1404	86	100	2904
X-ray sources	7	1	0	6	0	1	15
Unclear, others	1948	388	60	2432	174	133	5135

**Notes.** Three columns are given for both cluster types larger and smaller, respectively. The first column contains number of star with clear classification of variability type, the second column numbers of stars with uncertain classification denoted by a sign “:”. The third column numbers of unclearly classified stars noted by a sign “|”. The last column of the table contains sums of all stars of that variability class including unclear and uncertain classified ones.

**Table 4.** Numbers of types of variable stars in present variable star catalogues in the same form as explained in Table 3.

Type	GCVS			VSX		
Eruptive	4781	606	0	6005	1098	12
Pulsating	23 048	5120	0	78 970	13 254	6784
Rotating	1434	468	0	10 521	659	148
Cataclysmic	846	221	0	2406	486	23
Eclipsing	7616	748	0	44 083	1621	3123
X-ray sources	157	8	0	103	8	2
Unclear, others	757	280	0	54 335	3591	4142
Suma of stars	45 835			209 285		

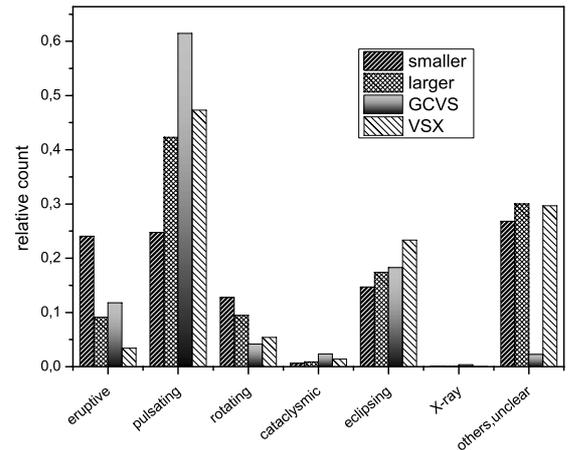
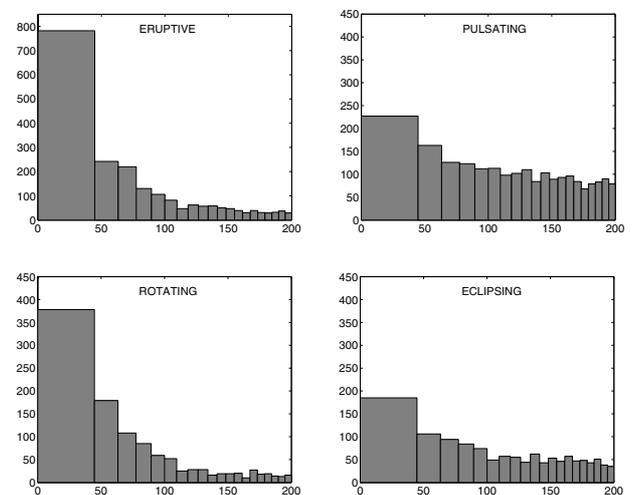
concentrated around the centres of open clusters, the pulsating stars are distributed much more evenly, which can be interpreted as a significant portion of these pulsating stars not belonging to the open clusters themselves. This interpretation is supported by the distribution of pulsating variables for larger open clusters, which is almost the same (182 variables) for all areas. We also inspected the distribution of the other types of star variability, rotating stars and eclipsing binaries (see Fig. 3). The distribution of rotating variables indicates that practically all these observed variables belong to clusters, while the distribution of eclipsing binaries resembles that of the distribution of pulsating stars with some relation to their “host” clusters.

However, some new photometric studies of open clusters (e.g. Sandquist et al. 2011; Janik et al. 2012; Lata et al. 2011) show that many variable stars in open clusters still need to be unveiled, so these statistical results could be significantly distorted due to the selection of only currently known variables.

#### 4. Conclusions

We have prepared a new catalogue of variable and suspected variable stars in open clusters and their close vicinities. This version of the catalogue is only the start of the project. The compiled lists of objects include stars that are located in the area of open clusters up to twice their published radii. Owing to the lack of accurate and homogeneous data, we were not able to extract detailed membership probabilities for all stars. However, we took a first step by including the proper motion of targets from the PPMXL catalogue, and we prepared a new catalogue of mean cluster proper motions.

The most numerous group of variable stars present in open clusters is the still unconfirmed or unspecified objects followed


**Fig. 2.** Relative numbers of basic star variability types in open clusters smaller and larger than 60', compared to the GCVS and VSX. The values are normalised to the number of variable stars in the given source of data.

**Fig. 3.** Distribution of the four most numerous groups of variable stars according to their distance from the centre of open clusters in cluster radii in open clusters smaller than 60' in diameter.

by the eruptive variables. The pulsating variables that dominate the cluster variable star population in open clusters larger than 60' are mostly field stars.

We are convinced that our catalogue with noted variability will significantly contribute towards further research on related topics. For example, we are able to determine the distance of an open cluster in several ways using variable stars (eclipsing binaries and/or pulsating stars). Thus, analysing one type of cluster target(s) will have a major impact on similar objects in the galactic field.

*Acknowledgements.* Part of this work was supported by the Czech grants GAP209/12/0217, 7AMB12AT003, WTZ CZ 10/2012, MUNI/A/0968/2009 and Austrian Research Fund via the project FWF P22691-N16. We appreciate the using of VSX Index of AAVSO. This research has made use of NASA’s Astrophysics Data System and the WEBDA database, operated at the Department of Theoretical Physics and Astrophysics of the Masaryk University. We thank S. de Villiers for valuable notes to the manuscript.

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