Stellar Cluster Candidates Discovered in the Magellanic System

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Abstract

We address the currently exciting issue of the presence of stellar clusters in the periphery of the Magellanic Clouds (MCs) and beyond by making use of a wealth of wide-field high-quality images released in advance from the Magellanic Stellar History (SMASH) survey. We conducted a sound search for new stellar cluster candidates from suitable kernel density estimators running for appropriate ranges of radii and stellar densities. In addition, we used a functional relationship to account for the completeness of the SMASH field sample analyzed that takes into account not only the number of fields used but also their particular spatial distribution; the present sample statistically represents \( \sim 50\% \) of the whole SMASH survey. The relative small number of new stellar cluster candidates identified, most of them distributed in the outer regions of the MCs, might suggest that the lack of detection of a larger number of new cluster candidates beyond the main bodies of the MCs could likely be the outcome once the survey is completed.

Key words: techniques: photometric – galaxies: individual (LMC-SMC) – galaxies: star clusters: general

1. Introduction

The Survey of Magellanic Stellar History (SMASH; Nidever & Smash Team 2015) is aimed at mapping the expected stellar debris and extended populations from interactions of the Magellanic System (MS) and the Milky Way (MW) with unprecedented fidelity. As stellar clusters are considered, some recent outcomes have shown that there are still a substantial number of extreme low-luminosity stellar clusters undetected in the wider MS periphery and the MW halo (Kim et al. 2015; Martin et al. 2016; Pieres et al. 2016). Furthermore, streams of gas and stars that might harbor stellar clusters have also been detected (Belokurov et al. 2016; Deason et al. 2016; Mackey et al. 2016).

As of 2016 October, 58 SMASH fields (each one is an array of sixty-two 2k \( \times \) 4k CCD detectors covering \( \sim 3 \) deg\(^2\) with an unbinned pixel scale of 0.27 arcsec) have been made publicly available from the National Optical Astronomy Observatory (NOAO) Science Data Management Archives.\(^3\) Figure 1 shows the distribution of the complete list of SMASH fields and those already observed and publicly available drawn with open and filled hexagons, respectively.

In this Letter, we make use in advance of this wealth of released images to anticipate some ultimate answers about the expected undetected stellar clusters in the Magellanic Clouds (MCs) periphery. In Section 2, we describe our search for new stellar cluster candidates, as well as a discussion of the results. Finally, Section 3 summarizes the main conclusions of this work.

2. Data Collection and Analysis

We downloaded calibrated, single-frame reduced images with the instrument signature removed and WCS calibrations applied according to the DECam Community Pipeline (Valdes et al. 2014). We prefer those reprojected images that have been corrected for distortion, etc., and are better astrometrically fixed. Finally, we filtered \( g \) images with exposure times longer than 267 s; the deepest images obtained by the DECam (Drlica-Wagner et al. 2016; Kim et al. 2016; Martin et al. 2016). Then, we run the DAOFINE routine within the DAOPHOT suite of programs (Stetson et al. 1990) to produce photometric catalogs of each \( \sim 2^{\circ} 2 \) FOV image down to \( g \sim 24.0 \) mag. Note that SMASH fields do not overlap those from the Dark Energy Survey (Dark Energy Survey Collaboration et al. 2016) and are deeper than the single \( g \) 90 s exposures of the Magellanic SatelLites Survey fields. (MagLiteS; Drlica-Wagner et al. 2016).

The strategy for searching new stellar clusters in the MS was developed in Piatti et al. (2016) with the aim of applying it to the whole VISTA\(^4\) near-infrared \( YJHK_s \) survey of the MCs system (VMC; Cioni et al. 2011) and was also used elsewhere (e.g., Piatti 2016). It executes a series of AstroML routines (Vanderplas et al. 2012 and reference therein for a detailed description of the complete AstroML package and user manual), a machine learning and data mining for Astronomy package. The method makes use of the range of radii and stellar densities of known Large and Small Malleganic Cloud (L/SMC) clusters, so that it is able to detect the smallest and/or less dense clusters in the MS. Piatti et al. (2016) searched for new star clusters in a pilot field of \( \sim 0.4 \) deg\(^2\) in the southwest side of the SMC bar, where the star field is the densest and highest reddened region in the galaxy. Based on the selection criteria mentioned above, they identified the 68 known star clusters located in that pilot field (Bica et al. 2008) and 38 new ones (\( \approx 55\% \) increase in the known star clusters located in the surveyed field). We refer the reader to Piatti et al. (2016) for quantitative details concerning detection efficiency, crowding effects, cluster mass, concentration, etc. We used here two different kernel density estimators (KDEs), namely, \textit{Gaussian} and \textit{tophat}, and bandwidths from 0.2 up to 1.0 arcmin.

From the total number of stellar overdensities detected per field, we merged the resulting lists, avoiding repeated findings from different runs with different bandwidths. We finally identified some new stellar cluster candidates in a few SMASH fields depicted in Figure 2 with thick magenta open hexagons,
where we also recognized the 533 known cataloged stellar clusters. From these results we conclude that it is hardly possible that any stellar cluster down to the known smallest and/or less dense limits of MC clusters has not been detected in the analyzed SMASH fields.

The coordinates of the new stellar cluster candidates are listed in Table 1, while 2 x 2 arcmin^2 g images centered on them are shown in Figure 3. As far as we are aware, these objects have not been included in previous peer-reviewed stellar cluster cataloging works. The estimation of their structural and fundamental parameters will be presented in a forthcoming paper (A. E. Piatti et al. 2017, in preparation). As can be seen, all of them are mainly located in the outer regions of the L/SMC main bodies; no stellar cluster candidate was detected beyond those regions. In Figure 2, we have included circles of 7.4 to 470 centered on the LMC and SMC, respectively, to illustrate the areas over which the new stellar cluster candidates are distributed. This result is in agreement with the positions of recently new stellar clusters detected toward the outermost northern LMC regions (Martin et al. 2016; Pieres et al. 2016), as well as stellar streams (Deason et al. 2016; Mackey et al. 2016 and references therein), in the sense that previously less explored outer regions of the L/SMC can harbor undetected stellar clusters.

The apparently small number of new stellar cluster candidates detected throughout 58 SMASH fields (~174 deg^2) caught our attention, since mapping the MS to a surface brightness limit of ~35 mag arcsec^{-2} (g ~ 24.0 mag; Nidever & Smash Team 2015) should result in an unprecedented deep stellar cluster survey. In order to evaluate the impact of such a small statistics of new stellar cluster candidates, in the context of the ambitious goals raised by SMASH, we estimated the completeness factor of the SMASH fields analyzed.

For analysis purposes we have distinguished three regions, called R1, R2, and R3, which were painted in Figure 1 with blue, red, and magenta colors, respectively. They embrace 13, 62, and 69 SMASH fields of which 4, 18, and 13 were used here for searching for new stellar clusters. Twenty-three other analyzed fields placed in the L/SMC main bodies are represented by black filled circles and were not considered in this estimate because we are interested in assessing our results...
for the MC periphery. Note also that the western side of the SMC has not been observed by SMASH yet, so it was not taken into account either.

The analyzed fields are distributed in such a way that they are not concentrated in a particular zone of the three regions, but rather across areas larger than that for the SMASH 20% filling factor. Because of this particular spatial distribution, the completeness factor of the analyzed fields depends on both the number of fields analyzed and their distribution within each region. The more the number of fields analyzed, the higher the completeness, so that the completeness results are proportional to the ratio between analyzed fields and the complete list of

| Field4-01 | Field10-01 | Field10-02 | Field10-03 |
|-----------|------------|------------|------------|
| Field11-01 | Field11-02 | Field11-03 | Field12-01 |
| Field15-01 | Field16-01 | Field16-02 | Field30-01 |
| Field30-02 | Field40-01 | Field40-02 | Field40-03 |

*Figure 3. 2 $\times$ 2 arcmin$^2$ $g$ images centered on the new MS stellar cluster candidates. North is up and east to the left.*
SMASH fields. On the other hand, the analyzed fields in a particular R region can be placed all together (at the filling factor) or spread throughout the whole R region, so that the completeness turns out higher as the area covered by the analyzed fields is statistically more similar to that of the R region.

In order to estimate such a completeness factor we used the expression:

$$\psi(k, p) = k/(1 - (p - k)^2) \quad p, k \in \{0, 1\}; \quad p \geq k,$$

where $k$ represents the ratio between filled and open hexagons (see Figure 1) and $p$ is a measure of the similarity between their spatial distributions, respectively. Note that when the analyzed fields are placed as close as possible, $p$ equals $k$, and when they spread throughout an R region, equals 1. Thus, the better an R area is covered by the analyzed fields, the higher the $p$-value.

The expression $(p - k)^2$ measures in quadrature the difference between the statistical spatial coverages given by $p$ and that when all the analyzed fields are placed together ($k$), so that $1 - (p - k)^2$ approaches the unity when $p$ is closer to $k$. Thus, for a fixed ratio of analyzed fields $k$, the completeness increases as the distance in quadrature between $p$ and $k$ increases as well. To evaluate $p$, we used the $kde.test$ statistical function provided by the $ks$ package (version 1.10.4). The function applies a two-dimensional KDE based algorithm, able to broadly assess the similarity between data in two different arrays. The result, quantified by a $p$-value, is the probability, assuming the null hypothesis is true, of observing a result at least as extreme as the value of the test statistic (Feigelson & Babu 2012). Here, the null hypothesis is that $(x, y)$ coordinate samples for filled and open hexagons come from the same underlying distribution, with a lower $p$-value indicative of a lower probability that the null hypothesis is true.

We obtained $p$-values of 0.98, 0.93, and 0.93, from which $\psi(k, p)$ resulted to be 0.56, 0.53, and 0.42 for R1, R2, and R3, respectively. The $p$-values show that the analyzed fields very well match the designed SMASH field distribution, with a lower spatial frequency though. Therefore, we can conclude that it is not obvious that a substantial number of undetected stellar clusters, compared to the number of new candidates identified here, populate the MC periphery. On the contrary, we speculate with the possibility that there could exist very few isolated stellar clusters in the MC periphery stripped out from their parent galaxies due to MCs/MW interactions (e.g., Hammer et al. 2015; Salem et al. 2015). This speculation could fuel the present debate about whether ultra-faint objects discovered in the MW halo are dark matter free (stellar cluster) or dark matter dominated (dwarf galaxy) objects (e.g., Kim et al. 2015; Martin et al. 2015; Contenta et al. 2016; Drlica-Wagner et al. 2016; Sales et al. 2017).

### 3. Conclusions

We made use of publicly available SMASH images to conduct a sound search for new stellar clusters in the MS. After building photometric catalogs from stars found by DAOFIND in each image, we embarked on such a huge, time-consuming challenge by employing density kernel estimators with appropriate bandwidths in order to detect the smallest and/or less dense clusters in the MS. We found 24 new stellar cluster candidates distributed in 11 different SMASH fields, most of them located in the outer regions of the L/SMC disks.
Although their spatial distribution confirms that the outer regions of the MC have been less explored in the past, their small number suggests that there would appear to be low chances of detecting a significant number of stellar clusters there.

Bearing in mind that the analyzed sample of SMASH fields is far from being complete, we estimated the completeness factor of them by using a completeness function that depends on both the number of fields analyzed and their spatial distribution. Because of such a particular spatial coverage, we found that the present sample—statistically speaking—nearly represents 50% of the whole survey. This means that the lack of detection of a larger number of new cluster candidates could likely be the outcome once the survey is completed.

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