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# New variable stars discovered in the fields of three Galactic open clusters using the VVV survey

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## HIGHLIGHTS

- We aim at searching new variable stars in the fields of Galactic open clusters.
- The search is performed using near-infrared data obtained from the VVV Survey.
- We discovered 157 new variable stars in the fields of three open clusters (Cepheids, RR Lyr, eclipsing binaries, etc.).
- We obtained fundamental parameters for a selected sample of binary systems.

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## ABSTRACT

This project is a massive near-infrared (NIR) search for variable stars in highly reddened and obscured open cluster (OC) fields projected on regions of the Galactic bulge and disk. The search is performed using photometric NIR data in the *J*-, *H*- and $K_s$- bands obtained from the Vista Variables in the Vía Láctea (VVV) Survey. We performed in each cluster field a variability search using Stetson's variability statistics to select the variable candidates. Later, those candidates were subjected to a frequency analysis using the Generalized Lomb-Scargle and the Phase Dispersion Minimization algorithms. The number of independent observations range between 63 and 73. The newly discovered variables in this study, 157 in total in three different known OCs, are classified based on their light curve shapes, periods, amplitudes and their location in the corresponding color-magnitude $(J-K_s, K_s)$ and color-color $(H-K_s, J-H)$ diagrams. We found 5 possible Cepheid stars which, based on the period-luminosity relation, are very likely type II Cepheids located behind the bulge. Among the newly discovered variables, there are eclipsing binaries, $\delta$ Scuti, as well as background RR Lyrae stars. Using the new version of the Wilson & Devinney code as well as the "Physics Of Eclipsing Binaries" (PHOEBE) code, we analyzed some of the best eclipsing binaries we discovered. Our results show that these studied systems turn out to be ranging from detached to double-contact binaries, with low eccentricities and high inclinations of approximately 80°. Their surface temperatures range between 3500 K and 8000 K.



## 1. Introduction

Star clusters are important building blocks of galaxies so knowledge of their individual and statistical properties is of great astrophysical importance. These populations, composed of stars sharing the same age and initial chemical composition, have allowed us to test theories of stellar evolution and have also helped to reveal the structure of their host galaxies. In particular, Galactic

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open clusters (OCs) have long been considered excellent targets not only to probe the Galactic disk population (Friel, 1995; Bica et al., 2006) but also to trace its chemical evolution (see, e.g., Chen et al., 2003, and references therein). Estimates indicate that the Milky Way currently hosts a total of about $2.5 \times 10^4$ or more OCs (Portegies Zwart et al., 2010). However, in the catalogue by Kharchenko et al. (2013, hereafter K13), only 2808 Galactic OCs have reasonable estimates of basic cluster parameters such as distance and age, as well as an estimation of the interstellar extinction. This number clearly represents a lower limit to the possible amount of clusters belonging to the Milky Way, if we take into account the recently found clusters and cluster candidates (see, e.g., Bica et al., 2003; Dutra et al., 2003; Borissova et al., 2011; 2014; Ramírez Alegría et al., 2014; 2016; Chené et al., 2013; Barbá et al., 2015) and the "still unseen" OCs, which are deeply embedded in obscured regions or are just too faint to be detected. Distances, masses, and ages for OCs are generally determined from color-magnitude diagrams (CMDs). However, observations of OCs projected on the Galactic bulge region are strongly affected by the effects of both interstellar reddening and high field stellar density (Valenti et al., 2007; Alonso-García et al., 2012). In these objects, the cluster main sequences appear not to be clearly visible, which reduces the accuracy of the relevant physical parameters derived from their CMDs. In these cases, it is very helpful to identify cluster member variable stars since these stars can provide a more precise measurement of the clusters' parameters (particularly their distances).

The current project, based on near-infrared (NIR) photometric data, is a search for stellar variability in the fields of Galactic OCs which lie in the highly reddened and obscured regions of the Galactic bulge and disk. As part of a massive search for variable stars in OCs, we characterize for the first time new variable stars detected in three Galactic OC regions located toward the inner Galaxy. For this purpose, we make use of the VISTA Variables in the Vía Láctea (VVV) Survey, which is an ESO Public NIR time-domain survey of the inner Milky Way (Minniti et al., 2010). VVV aims to map the Galactic bulge as well as an adjacent section of the mid-plane, covering stellar populations all the way to the Galactic center, including regions of intense star formation. This survey has been performing time-domain observations in the $K_s$-band for over 5 years (Saito et al., 2012) and provides an atlas of 562 square degrees of the sky in 5 wavebands ($ZYJHK_s$), encompassing about a billion objects.

The VVV Survey is discovering hundreds of new clusters, many of them being very distant and deeply embedded objects toward the inner Galaxy (see, e.g., Borissova et al., 2011; 2014; Chené et al., 2013; Ramírez Alegría et al., 2014; 2016). The relevant physical parameters (reddenings, distances, masses, luminosities, sizes and metallicities) for these new clusters are still poorly known or unknown. Our project aims at focusing on all OCs in the VVV survey area. In this first approach, we analyze a few known OCs with previously identified variables. We selected, on the one hand, two moderately young and extended OCs with a relatively high amount of catalogued variables in their fields (Zejda et al., 2012) and a considerable amount of new possible variable member candidates. On the other hand, we also selected an intermediate-age more compact OC with only a few known variable stars and some newly discovered variable candidates detected in our study. Because the clusters are projected onto high density stellar regions of the Galactic bulge, we are at present mainly focused on searching probable NIR counterparts of the already catalogued variable stars as well as searching new variables only discovered using the VVV data. The subsequent goals will be related to the clusters' analysis, i.e., to comparing the advantages and disadvantages of analyzing extended and compact OCs and selecting close and faint OCs to warrant their non saturation and usefulness for a future analysis of their proper motions. In addition, with the help of our new data, we aim at improving some of these clusters' parameters that appeared to be uncertain.

In this work we present the first results obtained for three OCs projected on the inner parts of the Galactic bulge, namely Antalova 1, ASCC 90 and ESO 393-15. We describe them in the next section together with the data collected from the VVV Survey. Section 4 details the variable stars found in the fields of these three OCs and their classification based on the obtained light curves. Data analysis and discussion as well as some future work is described in Section 5.

## 2. Data acquisition and selected targets

The observations were made as part of the VVV Survey. The VIRCAM camera on the 4.1 m VISTA telescope is an array of 16 NIR detectors which produce a combined image of $11.6' \times 11.6'$ with a pixel size of $0.34''$ (Dalton et al., 2006). The photometry and data reduction have been described in detail elsewhere (Saito et al., 2012; Dékány et al., 2013; Alonso-García et al., 2015). We briefly mention here that the individual VVV images were reduced, astrometrized and stacked by the Cambridge Astronomy Survey Unit (CASU) using the VISTA Data Flow System (VDFS) pipeline (Emerson et al., 2004; Irwin et al., 2004; Hambly et al., 2004), and the photometry has been calibrated onto the VISTA filter system. The aperture photometry has been made by CASU on the individual processed images, and generated light curves were then analyzed for variability (see Dékány et al., 2013; Alonso-García et al., 2015). PSF photometry for each OC in the different available images was extracted and later cross-matched to create the CMDs. A brief description of the selected targets as well as a summary of the previous results for the fields under investigation is given below.

### 2.1. Antalova 1

Antalova 1 (IAU designation C1725-315) is catalogued as a moderately young and metal-poor OC located in Scorpius at $\alpha_{2000}$ = 17 h 28 m 57 s, $\delta_{2000}$ = -31°34′48″; l = 355.86°, b = +1.64° (K13). It is projected on the inner bulge in the area named b345 in Saito et al. (2012). Antalova 1 has been classified as IV2pn in the Trumpler system (Archinal and Hynes, 2003), i.e., as an OC with the fourth highest concentration degree, a medium range of brightness of its stars and a scanty population. Kharchenko et al. (2005b, hereafter K05) published a catalogue of astrophysical data for 520 Galactic OCs - among them Antalova 1 - which could be identified in their All-Sky Compiled Catalogue of 2.5 million stars (ASCC-2.5). By applying homogeneous procedures and algorithms, K05 determined angular sizes and fundamental astrophysical parameters for their cluster sample. For Antalova 1, they estimated an angular radius of 13.5′, and obtained the following results: E(B-V) = 0.25, d = 850 pc and 316 Myr. It should be noted, however, that owing to the relatively bright limiting magnitude (V ∼ 12.5) of the ASCC-2.5, K05's sample does not include faint and generally remote or highly obscured OCs. More recently, using a combination of uniform kinematic and NIR photometric data gathered in the all-sky catalogue PPMXL (Roeser et al., 2010) and the 2MASS catalogue (Skrutskie et al., 2006), K13 reported exact positions, apparent radii, proper motions, reddenings, distances and ages for more than 2800 mostly confirmed OCs. For Antalova 1, they provided the parameters listed in Table 1. Conrad et al. (2014) identified Antalova 1 in the Radial Velocity Experiment (RAVE; Steinmetz et al., 2006) and determined its mean cluster metallicity as [M/H] = −0.66 ± 0.19 (Table 1) from a cleaned working sample. A total of 43 variable stars have been catalogued by Zejda et al. (2012, hereafter Z12) in the cluster field.