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Variable stars in the field of open cluster NGC 1039

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Here we present preliminary results from the search and study of variable stars based on space-based observation data from the TESS mission, focusing on the field of the open star cluster NGC 1039. The light curves of various types of variable stars located within the cluster field are analyzed. Using data from the Gaia DR3 release, we determined the probable members and fundamental parameters of the cluster, as well as assessed the likely membership of the identified 14 variable star candidates in the field NGC 1039.

Keywords: Open star clusters (1160), young star clusters (1833), variable stars (1761)

1 Introduction

The study of the nearest stellar population from the Sun, the nearest regions of star formation, is indeed of particular interest and difficult to overestimate, as it naturally extends to such natural formations as star clusters and associations. We are attracted primarily by the very opportunity to explore at once the physical and chemical properties of such a large number of gravitationally bound celestial bodies. Secondly, as accurate as possible knowledge of the basic properties and fundamental parameters of the nearest structures in our Galaxy, which instantly affects the understanding of it as a whole system. Thirdly, the focus on the applied future (Bailer-Jones, 2021) and fourthly due to the emerging possibilities of high-precision astrometric studies, Gaia DR3 (Cantat-Gaudin et al., 2020) more accurately identified sources of variability and discovered new previously unknown aspects of their nature.

We present the results of a study of the open star cluster (OC) NGC 1039 (M 34), located ($\alpha_{2000} = 02^h42^m07.4^s$, $\delta_{2000} = +42^\circ44'46''$) in the 2nd quadrant, in the Perseus constellation. The NGC 1039 cluster is located at a distance of 534 pc (Cantat-Gaudin et al., 2020) from the Sun and is part of the group of the closest OC to us (Kos, 2024; Pang et al., 2021). A group of 900 most likely cluster stars is

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Table 1 The key parameters of NGC 1039, as reported in the literature, alongside the results obtained in our study.

α_{2000}, deg	δ_{2000}, deg	Plx, mas	PM_{RA}, mas/yr	PM_{DEC}, mas/yr	E(B-V), mag	A_V, mag	log(age), year	$[Fe/H]$	Distance, pc	Ref.
40.478	42.791	–	0.39	–6.8	0.07	–	8.17	–0.3	499.0	1
40.55	42.79	–	-0.28	–6.73	0.077	–	8.383	0.07	510.0	2
40.515	42.762	–	-0.67	–6.12	0.071	–	8.239	–	503.96	3
40.519	42.777	–	–	–	–	–	–	–	–	4
40.531	42.722	–	–	–	–	0.239	8.101	0.0	513.33	5
40.531	42.722	1.949	0.722	–5.681	–	0.16	8.12	–	534.56	6
40.51	42.712	1.943	0.736	–5.695	–	0.328	8.425	0.006	507.0	7
40.468	42.718	1.986	0.691	–5.715	–	–	–	–	–	8
40.494	42.735	1.998	0.656	–5.788	–	–	8.15	–	525.0	9
40.544	42.732	2.007	0.646	–5.788	–	0.35	7.9	–	–	10
40.548	42.722	2.003	0.652	–5.791	–	0.143	8.087	–	476.43	11
40.5	42.713	2.006	–	–	–	0.37	8.1	0.27	505.82	12
40.533	42.762	2.039	0.613	–5.553	0.082	0.154	8.12	0.11	508.16	13

Notes: 1, Chen et al., 2003; 2, Kharchenko et al., 2012; 3, Loktin and Popova, 2017; 4, Bica et al., 2019; 5, Bossini et al., 2019; 6, Cantat-Gaudin et al., 2020; 7, Dias et al., 2021; 8, Jaehnig et al., 2021; 9, Tarricq, 2021; 10, He et al., 2022; 11, Hunt and Reffert, 2023; 12, Cavallo et al., 2024; 13, this work

scattered in an area with angular dimensions greater than $48'$ (Cantat-Gaudin et al., 2020). Estimates of the age of this young cluster range from 79 (He et al., 2022) to 266 million years (Dias et al., 2021) (see Table 1 for details).

In the first part of this paper we present the fundamental parameters of the NGC 1039 and a set of identified probable stars of the cluster. In the second part, we show the results of the search and study of variable stars of the cluster and its immediate surroundings in the OC region based on data from the TESS space mission (Stassun et al., 2019).

2 Data and methods: members determination

A data set with a field size of $1.916^\circ \times 1.916^\circ$ was prepared using standard Astroquery queries (Ginsburg et al., 2019) without restrictions and filters on star values and other parameters. A similar selection was carried out in order to obtain a more complete sample of all measured objects in this region in order to further search for probable variable stars located in the cluster region and determine their likely membership in the cluster. For bright stars that did not have Gaia DR3 proper motion data, the values were obtained from the PPMX catalog (Röser et al. 2008).

To exclude field stars, the pyUPMASK program (Pera et al., 2021), a Python implementation of the UPMASK algorithm (Krone-Martins and Moitinho, 2014) originally written in R, was employed. UPMASK is widely used by the Gaia collaboration for the automatic processing of astrometric and photometric data. In this study, the method outlined by Chi et al. (2023) for using pyUPMASK was applied. This method

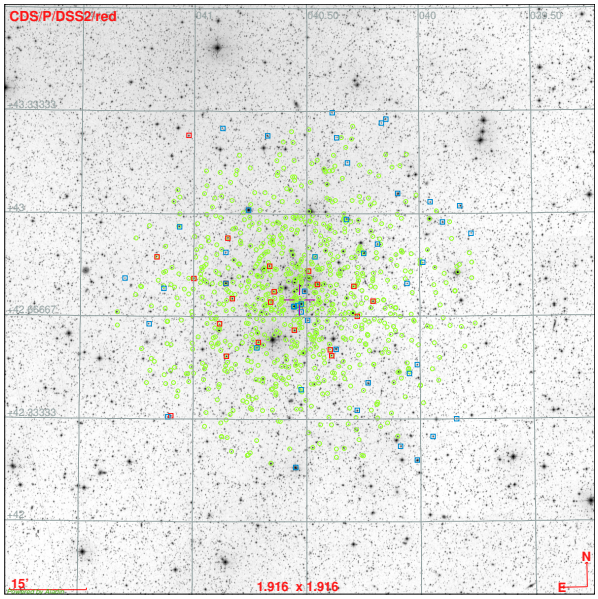


Figure 1 Spatial distribution of objects in the vicinity of the OC NGC 1039. Bright green circles represent stars with a membership probability greater than 95%, indicating high-confidence cluster members. Red squares denote candidate cluster stars that are likely to be variable. Blue squares highlight candidate variable field stars. For further details, refer to the text.

involves a two-stage process for the exclusion of field stars. In the first stage, two sets of parameters are utilized: coordinates relative to the cluster center and proper motion values. The second stage utilizes additional stellar parameters as filtering criteria, including celestial coordinates, proper motions, parallaxes, Gaia photometry, and the probability of cluster membership, as determined in the first stage. The outcome of the pyUPMASK procedure is illustrated in Figs 1 and 2.

3 Fundamental parameters of the NGC 1039

To determine the fundamental parameters of the cluster, we utilized the ASteCA automated star cluster analysis package (Perren et al., 2020). The tasks performed by ASteCA can be broadly categorized into three primary analytical blocks: (1) the investigation of the spatial structure of the cluster, including the identification of the cluster region based on increased stellar density; (2) the assessment of the cluster's center and the probability of membership for stars within the high-density region; and (3) the optimization of parameter values to best fit the observed data. ASteCA provides estimates for key cluster parameters, including metallicity, age, reddening, and distance. To prepare a set of theoretical isochrones from the PARSEC model (Bressan et al., 2012), which serves as the basis for ASteCA's analysis, the online

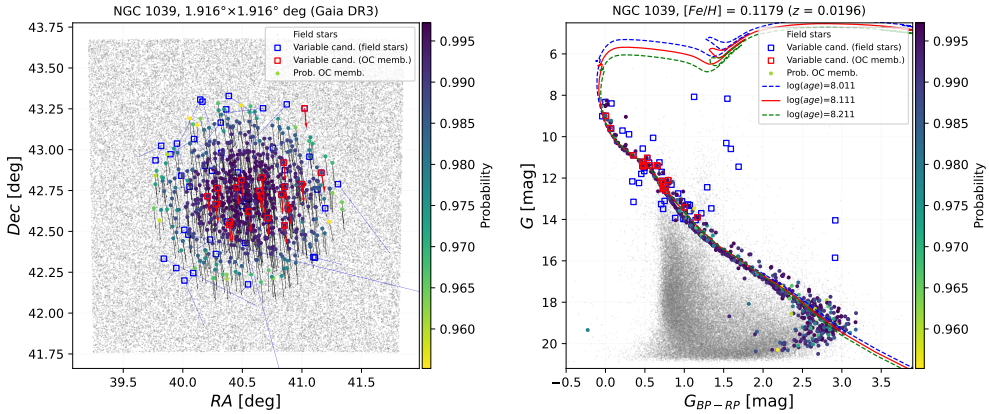


Figure 2 Spatial distribution of stars in the NGC 1039 cluster region (left) and the corresponding color–magnitude diagram (CMD) (right), with candidate variable stars indicated by colored square symbols. The color bar represents the membership probabilities of the selected open cluster (OC) stars.

CMD 3.8 form provided by the Padovan Astronomical Observatory[1] was utilized. For the conversion of metallicity $[Fe/H]$ to z units, we used the Python-based isodist.[2] software package, using the solar metallicity $z_{\odot}$, which was adopted as 0.0152 (Bressan et al., 2012).

Table 1 presents the key parameters of the star cluster NGC 1039 reported in the literature, alongside the corresponding values obtained in this study.

4 Variable stars in the open cluster region NGC 1039

Data obtained from the Transiting Exoplanet Survey Satellite (TESS) mission were used to investigate variable stars within the open cluster NGC 1039. The analysis was conducted using the Lightkurve software package (Lightkurve Collaboration et al., 2018), a community-developed, open-source Python package that provides a user-friendly platform for the reduction and analysis of time-series photometric data. This package facilitates the programmatic retrieval of observational data from space-based missions such as Kepler and TESS through their respective archives. It allows for the extraction of photometric time series, the construction of light curves using customizable aperture masks, and the visualization of data products. Furthermore, Lightkurve offers a suite of tools for light-curve manipulation, including phase folding, binning, detrending, and the removal of systematic artifacts. The software also supports the generation of various types of periodograms to assist in detecting periodic variability (Lenz and Breger, 2014).

Data were downloaded from the Mikulski Archive for Space Telescopes (MAST) portal [3], including high-level science products (HLSPs) from the MIT Quick Look

[1] https://stev.oapd.inaf.it/cgi-bin/cmd
[2] https://github.com/jobovy/isodist
[3] https://mast.stsci.edu/portal/Mashup/Clients/Mast/Portal.html

Pipeline (Huang et al., 2020a, 2020b) for 849 objects located within a 0.65° radius of the cluster area. We utilized data from sector 85, obtained in 2024 over 27 days. To search for periodic variations, Lomb-Scargle periodograms (Lomb, 1976; Scargle, 1982) were applied. After analyzing the light curves, we identified 82 objects that exhibit noticeable variations. This selected list of stars was then compared with known variable stars in the region, as reported in the literature and open data sources (Gavras et al., 2023; Samus' et al., 2017; Watson et al., 2017).

5 Discussion and conclusions

The selection of probable cluster members is consistent with the set of probable cluster stars identified in previous studies (Cantat-Gaudin et al., 2020; Dias et al., 2021). This selection indicates that within the 1.916° × 1.916° region, we identified 1,224 stars, which are likely members of the cluster with a probability greater than 70%, of which 759 have a probability of 95% or higher. The field star filtering method presented above provides a confident and comparable result.

The sample was then compared with a set of selected probable variable stars in the region, including those identified by other authors. Among the 82 stars selected as probable variable star candidates within the NGC 1039 cluster region, the light curves of 18 stars are artifacts, influenced by the proximity of a nearby variable star. This effect is attributed to the large angular size of the CCD pixels in the TESS mission detectors and does not reflect any intrinsic variability in the stars' brightness. Of the remaining 64 stars, 13 were classified as various types of eclipsing variables, 1 as a probable semiregular variable, 6 as rotating variables, 29 as various types of pulsating variables, and the cause of variability remains unknown for 14 stars. Additionally, 30 of the selected probable variable stars are previously known variable stars of various types.

The list of candidate variable stars, which are likely members of the open cluster, is presented in Table 2, with well-known variable stars marked with a checkmark in the final column. For four objects that overlap in the frames, it was not possible to determine exactly which star in each pair is variable (302146320, 302083493, 307477140, 643919227). Three of these stars are field stars. Among the selected probable variable stars, 21 are likely members of the cluster. According to data from the AAVSO database (Watson et al., 2017), several dozen additional known variable stars are located within the cluster field. However, we were unable to detect any significant variability in these stars within the sample analyzed in this study, probably due to the limitations of the sample size and the presence of systematic artifacts in the TESS light curves. The positions of the probable variable stars on the Hertzsprung-Russell diagram, along with their spatial distribution, are shown in Fig. 2. Examples of light curves for several new candidate variable stars are presented in Fig. 3.

Table 2 The probable open cluster members of NGC 1039 may be potential candidates for newly identified variable stars.

TIC	α_{2000}, deg	δ_{2000}, deg	Period, days	$T_{\rm mag}$, mag	Amplitude, mag	Variable, type	Known var.
20708249	41.16307890457	42.85870215622	0.82608	11.763	0.0061	GDOR:	
302083345	40.49115298456	42.81344869778	1.37163	12.2105	0.0222	BY:	
302083436	40.64404190535	42.7474552586	0.77687	11.1865	0.0089	GDOR:	✓
302083568	40.55421696209	42.62134934432	0.04633	10.7529	0.0041	DSCT:	
302084883	40.71145950313	42.58168473867	0.31939	10.9742	0.0048	GDOR:	
302085023	40.65781091928	42.71366904344	1.0927	11.8548	0.0094		
302085158	40.66274953325	42.82973968217	0.32747	11.0915	0.0066	DSCT:	✓
302145477	41.02298116578	43.2531025737	0.22755	11.108	0.004	DSCT:	✓
302145920	40.99898224966	42.78943591865	0.45037	11.1516	0.0047	GDOR:	
302146320	41.09634960377	42.34283828022	0.94154	12.7529	0.0226	GDOR:	
307476906	40.85305653853	42.53638926607	1.11366	11.0412	0.0064	GDOR:	
307477002	40.88317106939	42.64209978876	0.81188	12.8958	0.0297	ROT:	✓
307477096	40.82891159489	42.72463996149	0.40631	11.1758	0.008	DSCT:	✓
307477137	40.85678956915	42.77295248432	1.17107	9.5923	0.0022		
307477283	40.84788346291	42.92093437995	1.05168	12.0736	0.009	GDOR:	
399582163	40.38994923536	42.53955316149	1.90992	11.6854	0.0069		
399582180	40.3961721455	42.55860615428	0.38432	13.2972	0.0183	BY	✓
399582437	40.45201648319	42.77060594905	0.78506	9.0305	0.0034	GDOR:	
422923054	40.27651866681	42.66662941103	0.02816	10.7281	0.007	DSCT	
422923098	40.20592694111	42.71517348828	1.82627	11.069	0.0117		
422923142	40.29125758774	42.76484524862	1.32284	12.1436	0.0074	BY	✓

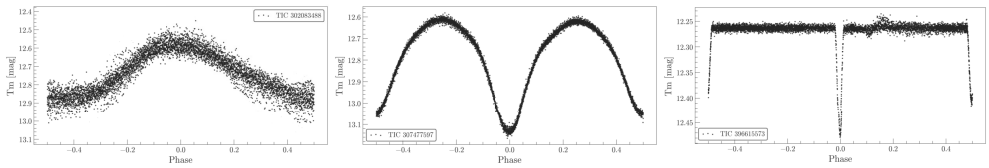


Figure 3 Examples of light curves for several variable stars.

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