Variability Survey of Southern Open Clusters NGC 6134, NGC 6416, Collinder 394, and Alessi 10

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Abstract. We present the results of a brightness variability survey of four southern open clusters, namely NGC 6134, NGC 6416, Collinder 394, and Alessi 10, which were observed using three telescopes following a time series photometric scheme during the dry season in 2022. The purpose of these observations was to detect variability events and their types of variability in star members of these four clusters. Data analysis was performed using a differential photometry method to produce light curves. Several new variable star candidates were discovered in the observed clusters. More observational data are needed to examine the consistency of the variabilities, estimate relevant periodicity, and determine the type of variable star.

Keywords: *differential photometry; eclipsing binary; exoplanet; southern open cluster; variable star.*

1 Introduction

Stars evolve in such a way that the light they emit changes during their lifetime. On shorter time scales, stars also show changes in their brightness, which can be caused by physical changes in the stellar interior at certain phases of their evolution or more frequent activities at their surfaces. Changes in a star's brightness can also be caused by obscuration by companion objects, such as companion stars or their planetary system. These changes caused by external factors are known as binary star eclipses and exoplanet transits.

Received August 6th, 2024, Revised January 19th, 2026, Accepted for publication January 19th, 2026
 ISSN: 2337-5760,
DOI: 10.5614/j.math.fund.sci.2026.57.3.1

Open clusters consist of stars which were formed within the same epoch and origin. Therefore studying variable stars in open clusters is more advantageous than field stars, because the parameters of distance, age, chemical composition, and reddening can be cross-checked statistically and thus better estimated. From the point of view of observational technique, simultaneous CCD photometry of all stars in the entire cluster field enables us to carry out efficient observations. One can obtain accurate time series data by observing the stars under the same weather conditions to prescribe homogenous correction due to local observational conditions [1].

With this observation survey, we aimed to detect stellar brightness variability in open clusters. The main goal was to find new variable star candidates in four southern open clusters. The long-term goal was to determine the variable star populations in each of these open star clusters. The presence of a number of variable stars in open clusters will help to better understand the relationship between variability and the evolutionary stage of stars.

Using the same data, we looked for exoplanetary transit events. Based on the exoplanet.eu database, the number of exoplanet discoveries in open clusters amounts to less than 1% of the 6,856 [2] exoplanets that have been discovered to date, which is too small if one believes that a significant number of stars in the galaxy are formed in clusters [3]. The discovery of exoplanets in open star clusters in this work will help reduce the discrepancy between planetary system formation theories and observational findings.

2 Observations and Data Reductions

Observations were carried out using the BRT (Bosscha Robotic Telescope) [4] and STEVia (Survey Telescope for Exoplanets and Variable Stars) [5] instruments located at the Bosscha Observatory located in Lembang, Indonesia.

Table 1 Instrument specification.

	BRT*	**STEVia**	**T72 iTelescope**
Optic type	Ritchey-Chretien	Schmidt-Cassegrain	Corrected Dall-Kirkham
Mirror diameter	40.6 cm	28 cm	50 cm
Focal ratio	f/8	f/6.3	f/6.8
CCD camera	QSI 616	SBIG ST-8 XME	FLI PL16200
Filter	Bessel R	Bessel R	Bessel R
Field of view	12' x 9'	26.7' x 17.8'	26.93' x 21.53'
Resolution	0.57"/pixel	1.055"/pixel	0.359" /pixel

*) BRT system with GSO 16" OTA and QSI 616 CCD camera

We also used the T72 telescope from the iTelescope facility at the Rio Hurtado Observatory, Chile, to complement the observational data from Bosscha Observatory. The specifications of the three telescopes are given in Table 1.

This work is part of the variability survey program on southern open clusters at Bosscha Observatory. The observed open clusters were selected based on the following criteria: 1) the cluster has an angular extent < 30 arc minutes and a brightness of V < 12 magnitudes; 2) the cluster's position is at least 30° above the horizon during observation; 3) the star membership of the cluster is known – we used the WEBDA[1)] database as a reference to identify each open cluster's star members; and 4) the age of the open cluster is more than 50 million years, which is the estimated age when a star cluster is clear of clouds left over from the formation of a planetary system. The last criterion aimed to accommodate the detection of transiting exoplanets.

Based on these four criteria, the open clusters we observed in this work are NGC 6134, NGC 6416, Collinder 394, and Alessi 10. Some basic parameters of these clusters and the allocation of instruments used in observing each cluster are given in Table 2.

Table 2 List of observed open clusters.

Cluster Name	RA (J2000) (hh:mm:ss)	Dec (J2000) (deg:mm:ss)	log age	Diameter (arc min)	Instruments used
NGC 6134	16 27 46	-49 09 06	8.968	**26.4**	BRT
NGC 6416	17 44 19	-32 21 42	8.087	**28.8**	STEVia
Collinder 394	18 52 28	-20 19 00	7.803	**36**	STEVia
Alessi 10	20 04 44	-10 28 47	8.71	**15**	STEVia & T72

We observed these four open clusters during the dry season of 2022. By limiting the height of the cluster during observations to > 30° from the horizon, we obtained a maximum allocation of 8 hours of observation time per night. Each open cluster was allocated 30 nights of observation time. Observations using the T72 telescope at the iTelescope facility were carried out only for four nights.

We applied a differential photometry method in the analysis process to produce the light curve of all the detected stars. Data processing was done using a photometry pipeline developed independently at the Bosscha Observatory. This photometry pipeline was developed based on the Lemon photometry pipeline [6]. This pipeline performs standard reduction, astrometric measurements, differential photometry, and constructs light curves. In the differential photometry section, the program measures the brightness changes of all stars in the field image. The stars with the smallest brightness changes are then used as reference stars. The relative brightness changes of other stars are measured against these reference stars.

[1] https://webda.physics.muni.cz/

Detection of variability in the light curves is done via visual inspection, while a grading system is used to assess the quality of the light curves. Grade A is assigned to light curves that have clear variable star patterns with complete and repeating cycles in the available observational data. The light curves must have at least two complete cycles of variability for the period of variability to be determined. We used the Vstar software with the Date Compensated Discrete Fourier Transform (DCDFT) method to determine the variability period [7]. Using the obtained variability period, a phase-folded light curve can be generated. This phase-folded light curve is used to determine the type of variable star.

Grade B is assigned to light curves with consistent variability at different observation times. The variability patterns can be recognized, but the light curve consists of only one variable cycle or even an incomplete cycle. Grade B light curves are intended for long-period variable stars that require long observation times.

Grade C is assigned to light curves that show irregular and inconsistent variability at different observation times. The known typical patterns of variable stars are difficult to recognize in grade C light curves. Grade C light curves could potentially originate from long-period variable stars or non-periodic events.

We checked the ASAS-SN[2)] and SIMBAD[3)] databases to identify whether the variability we detected had been discovered previously by other observations.

3 Results

3.1 Quality of Photometric Data

The dry season of 2022 did not provide us with favorable sky conditions for photometric observations. In this work, we used good quality data that only covers ~55% of the total available observational data (Table 3). The variability detected in the light curve varies with an amplitude ranging from 10 to 100 millimagnitudes, which is not always visible when low-quality data are included.

Table 3 Observation logs for good quality data.

	Exposure (s)	Obs. Length (h)	Selected data		Min. amplitude detected (mmag)
			Length (h)	%	
NGC 6134	40	16.93	11.17	65.98	20
NGC 6416	20 & 30	31.67	17.22	54.37	30
Collinder 394	20 & 30	30.05	12.25	40.76	100
Alessi 10	14, 30 & 40	11.36	6.98	61.44	10

[2] https://asas-sn.osu.edu/variables
[3] https://simbad.u-strasbg.fr/simbad/

3.2 NGC 6134 and Alessi 10

In the NGC 6134 cluster, we detected 12 stars showing variability (Table 4). Based on the ASAS-SN database, stars A3 and A7 are known to be pulsating variable stars of the Delta Scuti-type ([8],[9],[10]); stars A5 and A11 are long-period variable stars of the rotating type [9]; star A6 is a β Persei-type eclipsing binary star with a period of 0.974 days [9]. Unfortunately, our observational data does not cover a full eclipse event of this star, only an eclipse egress event (shown in star A6's second light curve in Figure 1). So far, star A9 is the only star to be a potential candidate for a newly discovered variable star in the NGC 6134 cluster. The other stars with grade C light curves slightly showed the pattern of a pulsating variable star. There is a non-zero possibility that some grade C light curves originate from long-period variable stars or eclipsing binary stars for which no eclipse event was observed.

Table 4 List of detected variability in NGC 6134.

ID	RA (2000)	Dec (2000)	Lightcurve Grade	Cluster member	Ref
A1	16 27 53.4	-49 02 41.0	C	No	This work
A2	16 27 35.5	-49 06 29.0	C	Yes	This work
A3	16 27 49.1	-49 06 43.2	B	Yes	[8][9]
A4	16 27 46.6	-49 08 23.2	C	Yes	This work
A5	16 27 38.7	-49 08 51.2	B	Yes	[9]
A6	16 27 37.8	-49 10 42.4	C	Yes	[9]
A7	16 27 48.7	-49 10 43.3	B	Yes	[8][10]
A8	16 28 13.8	-49 11 29.5	C	Yes	This work
A9	16 28 03.4	-49 11 53.7	B	Yes	This work
A10	16 27 26.0	-49 12 35.6	C	Yes	This work
A11	16 28 16.4	-49 12 49.1	C	Yes	[9]
A12	16 28 16.2	-49 13 49.8	C	Yes	This work

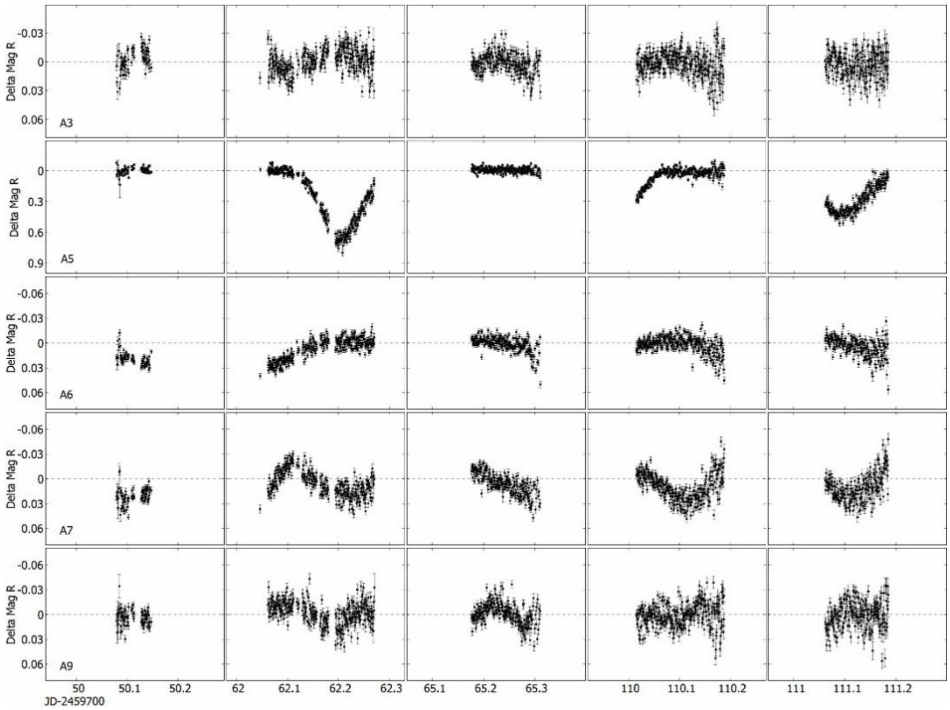

Figure 1 Grade B (stars A3, A5, A7, and A9) and the best grade C (star A6) light curves from observations of the NGC 6134 cluster.

We detected seven stars showing variability in the Alessi 10 cluster (Table 5). The ASAS-SN database shows that stars B4 and B6 are eclipsing binary stars of the β Lyrae-type that have orbital periods of 0.4 days [10] and 0.43 days [9], respectively. The WEBDA database shows that stars B4 and B6 are not members of the Alessi10 cluster.

Table 5 List of detected variability in Alessi 10.

ID	RA (2000)	Dec (2000)	Lightcurve Grade	Cluster member	ref
B1	20 05 00.4	-10 34 52.0	C	Yes	This work
B2	20 04 38.3	-10 33 55.4	C	Yes	This work
B3	20 04 23.5	-10 33 10.4	A	Yes	This work
B4	20 04 46.7	-10 30 07.6	B	No	[10]
B5	20 04 42.1	-10 29 50.6	A	Yes	This work
B6	20 04 39.2	-10 26 18.6	B	No	[9]
B7	20 04 37.1	-10 23 49.2	B	Yes	This work

We have good quality light curves of stars B3, B5, and B7 (Figure 2), which are potential candidates for new variable stars. Stars B3 and B5 appear to be short-period variable stars, with several cycles detected in their variability in a single night of observation. The process of determining the periods for these two stars produced values of 0.032 days and 0.033 days, respectively. The folded light curves of these two stars can be seen in Figure 3. We were not able to determine which type of variable stars these two are. The shape of the folded light curves of stars B3 and B5 appear to the inverse of that of the Delta Scuti variable star. The short periods of variability of these two stars indicate that they are not pulsating variable stars. Such a short period, ~46 minutes, falls within the range of cataclysmic variable stars. These are close binary star systems consisting of a white dwarf and a low-mass star. Based on its incomplete light curve, B7 appears to be a longer-period variable star. Judging by the shape of the light curve, B7's variability period is likely less than 1 day.

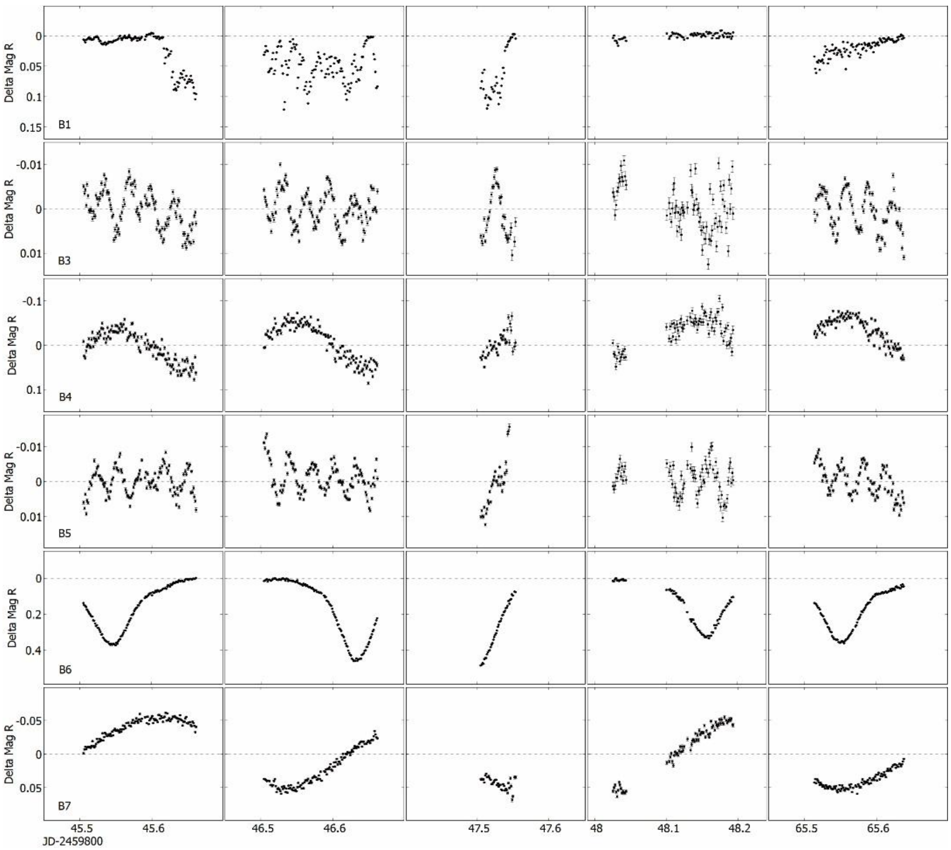

Figure 2 Grade A (star B3 and B5), grade B (star B4, B6, and B7) and the best grade C (star B1) light curves from observation of the Alessi 10 cluster.

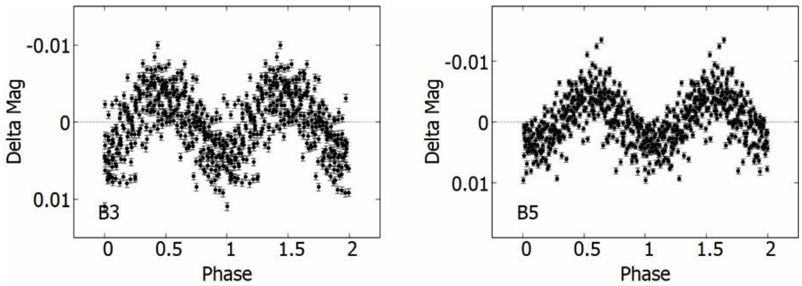

Figure 3 Phase folded light curves of star B3 (left) and star B5 (right).

3.3 NGC 6416 and Collinder 394

During observations of these two open clusters, the weather conditions at the Bosscha Observatory were not good, so that the best light curve only reached grade B quality. We detected 8 stars in the observation data of the NGC 6416 cluster that showed a variability similar to that of variable stars (Table 6). Star C2 is known to be an Algol-type eclipsing binary star with an orbital period of 5.23 days [10]. Star C8 has the potential to be a candidate for a new eclipsing binary star, as we could detect four eclipse-like events with two different dip values. We estimated deltas values of 0.15 mag for the primary eclipse and 0.1 mag for the secondary eclipse. The light curves for stars C2 and C8 are shown in Figure 4.

Table 6 List of detected variability in NGC 6416.

ID	RA (J2000)	Dec (J2000)	Lightcurve Grade	Cluster member	Ref
C1	17 44 52.2	-32 14 06.5	C	Yes	This work
C2	17 44 24.1	-32 16 45.1	B	Yes	[10]
C3	17 44 20.4	-32 17 07.2	C	Yes	This work
C4	17 44 41.2	-32 18 28.7	C	Yes	This work
C5	17 43 54.8	-32 19 05.0	C	Yes	This work
C6	17 44 07.7	-32 21 49.5	C	Yes	This work
C7	17 44 23.1	-32 22 25.6	C	Yes	This work
C8	17 44 39.0	-32 29 16.1	B	Yes	This work

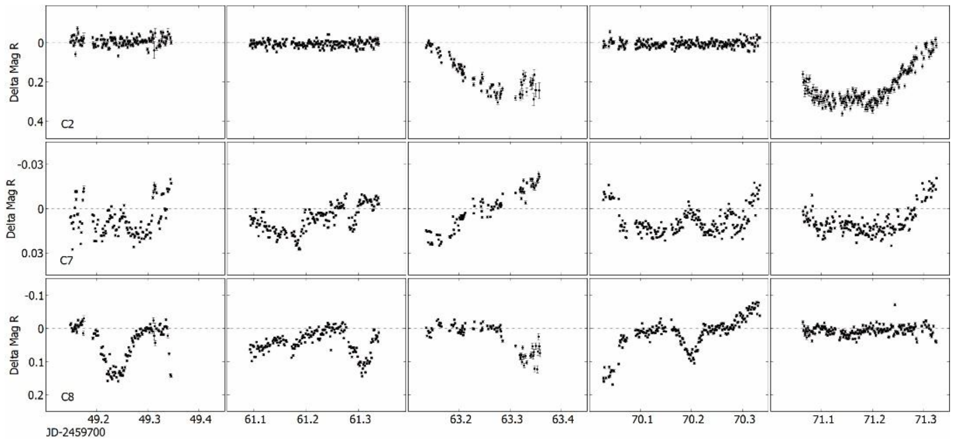

Figure 4 Grade B (star C2 and C8) and the best grade C (star C7) light curves from observations of the NGC 6416 cluster.

For the Collinder 394 cluster, we only got grade C-quality light curves (Table 7). Most variabilities that may resemble that of variable stars only occurred on one observation night and was of short duration. All stars in the field that showed variability in their light curves are background stars [11]. The best grade C light curve that we obtained from the observations of the Collinder 394 cluster can be seen in Figure 5.

Table 7 List of detected variability in Collinder 394.

ID	RA	Dec	Light curve grade	Cluster member	ref
D1	18 52 44.0	-20 08 22.0	C	No	This work
D2	18 53 10.1	-20 12 15.5	C	No	This work
D3	18 52 45.1	-20 13 20.6	C	No	This work
D4	18 53 03.9	-20 15 20.5	C	No	This work

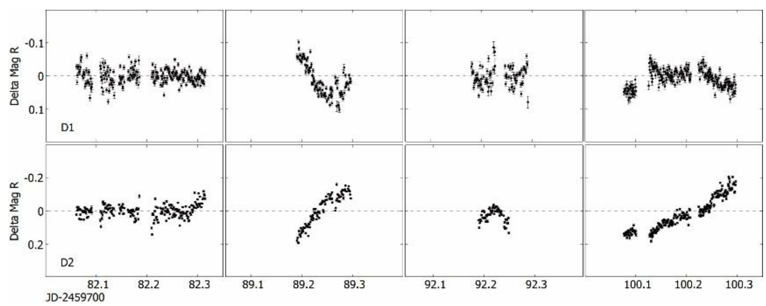

Figure 5 The best grade C light curves from observations of the Collinder 394 cluster.

4 Conclusion

In this variability survey, we observed four open clusters during the dry season of 2022 at the Bosscha Observatory located in Lembang, Indonesia. Despite the limited amount of good quality photometric data, several new variable star candidates were discovered. Further observations need to be made, especially for the stars with grade A and B light curves. A complete light curve covering at least two variable cycles for each candidate is needed to determine a reliable period of variability. A better time resolution of observational data is also required to identify the sub-types of pulsating variable stars or eclipsing binary stars that have been discovered.

Grade C light curves are often produced by stars located in dense areas. There is some possibility that the variability is caused by contamination from the light of nearby stars. However, it is possible that a grade C light curve originates from a non-periodic event. More observations are needed to distinguish the causes of the detected variability, whether by the quality of the observational data, by the target star's environment, or by the physical condition of the observed star.

So far, we have not detected any exoplanet transit event in the observed star clusters. Only a few good quality observational data sets at the Bosscha Observatory achieved photometric precision of less than 30 millimagnitudes, which is necessary to detect exoplanetary transit events. Although the observational data from Chile had better photometric precision, no exoplanet transit event was detected there. This could be due to our only acquiring 4 nights of non-consecutive observation data with an observation duration of 4 hours per night.

Another interesting matter for further study that we found in this work is the membership of the stars in the Alessi 10 cluster. The WEBDA database cluster chart shows that Alessi 10 has 12 members. This number is too small for an open cluster. Further observations may help to better define member stars or clarify Alessi 10's status as an open cluster or stellar association.

Acknowledgements

We thank the support from the Faculty of Mathematics and Natural Sciences of the Institut Teknologi Bandung through the PPMI KK Astronomi 2022 research grant. This research made use of the WEBDA database, operated by the Department of Theoretical Physics and Astrophysics of the Masaryk University. This research also benefited from the SIMBAD database, operated at CDS, Strasbourg, France.

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