Variable Stars in the 50BiN Open Cluster Survey. III. NGC 884 Postprint

Authors: Lin-Hong Wang, Qian-Heng Nie, Kun Wang, Xiao-Dian Chen, Chun-Guang Zhang, Li-Cai Deng, Xiao-Bin Zhang and Tian-Lu Chen

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Abstract

Open clusters are the basic building blocks that serve as a laboratory for the study of young stellar populations in the Milky Way. Variable stars in open clusters provide a unique way to accurately probe the internal structure, temporal and dynamical evolutionary stages of individual stars and the host cluster. The most powerful tool for such studies is time-domain photometric observations. This paper follows the route of our previous work, concentrating on a photometric search for variable stars in NGC 884. The target cluster is the companion of NGC 869, forming the well-known double cluster system that is gravitationally bound. From the observation run in 2016 November, a total of 9247 B-band CCD images and 8218 V-band CCD images were obtained. We detected a total of 15 stars with variability in visual brightness, including five Be stars, three eclipsing binaries, and seven of unknown types. Two new variable stars were discovered in this work. We also compared the variable star content of NGC 884 with its companion NGC 869.

Full Text

Preamble

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Lin-Hong Wang[1],[2],[3],[4], Qian-Heng Nie[3],[5], Kun Wang[6], Xiao-Dian Chen[3],[4],[6], Chun-Guang Zhang[3],[4],[6], Li-Cai Deng[3],[4],[6], Xiao-Bin Zhang[3],[4],[6], and Tian-Lu Chen[1],[2]

[1] School of Physics, Tibet University, Lhasa 850000, China; wanglinhong@tibet.edu.cn
[2] Key Laboratory of Cosmic Rays, Tibet University, Ministry of Education, Lhasa 850000, China
[3] Key Laboratory of Optical Astronomy, National Astronomical Observatories,

Chinese Academy of Sciences, Beijing 100101, China; licai@bao.ac.cn
[4] School of Astronomy and Space Science, University of Chinese Academy of Sciences, Beijing 100049, China
[5] School of Physics and Astronomy, Sun Yat-sen University, Zhuhai 519082, China
[6] School of Physics and Astronomy, China West Normal University, Nanchong 637002, China

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Abstract

Open clusters are fundamental building blocks that serve as laboratories for studying young stellar populations in the Milky Way. Variable stars within open clusters provide a unique means to accurately probe the internal structure, temporal behavior, and dynamical evolutionary stages of both individual stars and their host clusters. Time-domain photometric observations represent the most powerful tool for such studies. This paper continues the work presented in our previous studies, focusing on a photometric search for variable stars in NGC 884. As the companion to NGC 869, this target forms the well-known gravitationally bound double cluster system. From observations conducted in November 2016, we obtained a total of 9,247 CCD images in the B band and 8,218 in the V band. We detected 15 stars exhibiting visual brightness variability, including five Be stars, three eclipsing binaries, and seven of unknown type. Two of these variable stars are new discoveries. We also compared the variable star content of NGC 884 with that of its companion cluster NGC 869.

Key words: stars: variables: general -(Galaxy:) open clusters and associations: individual (NGC 884, NGC 869) -(stars:) binaries: general

1. Introduction

Members of an open cluster (OC) are believed to have formed within the same molecular cloud, sharing similar ages, chemical abundances, and essentially identical distances from Earth (Lada et al. 1993; Friel 1995). These properties make open clusters ideal laboratories for establishing and testing theories of stellar structure and evolution (Evans et al. 2009; Granada et al. 2018). Furthermore, various types of variable stars in open clusters provide additional tools for studying fundamental stellar parameters and internal structures that would otherwise remain hidden from direct observation. Exotic objects that deviate from standard stellar evolutionary theory are also common in open clusters, such as blue stragglers and hot subdwarfs. Pulsating variables and certain binary systems offer unique probes into stellar interiors and provide information about age and surface gravity. For example, Geller & Mathieu (2011) elucidated the mass exchange origin of blue straggler stars in NGC 188 by estimating the masses of their eclipsing binary companions. The study of variable stars has extensive applications across astronomy and cosmology. Classical Cepheid variables, for instance, serve as standard candles for measuring galactic distances and determining the precise structure of the Milky Way. Chen et al. (2019) employed Cepheids to construct the first intuitive three-dimensional map of the Galactic stellar disk, thereby discovering the warp and its precession.

NGC 884 in Perseus is a sparse, young cluster that, together with NGC 869, forms the famous Perseus double cluster (also designated h and Persei based on their morphological positions). This double cluster system has been the subject of extensive research. As early as 1937, Oosterhoff (1937) investigated the system using photographic plates. Subsequent studies employing modern CCD photometry and spectroscopic techniques have determined the fundamental physical parameters of the double cluster, including a reddening of $E(B-V) = 0.52$-0.56 mag (Slesnick et al. 2002; Currie et al. 2010), a distance modulus of 11.75-11.85 mag, and an age of $\log(\mathrm{Age}) = 7.07$-$7.20$ (Keller et al. 2001; Currie et al. 2010). More recently, Zhong et al. (2019) utilized data from Gaia Data Release 2 (DR2) to map the distribution of member stars in the double clusters and discovered a possible extended filamentary substructure associated with the system, indicating active dynamical interactions.

The 50 cm Binocular Network telescope (50BiN) is a dedicated facility for time-domain studies of open clusters (Deng et al. 2013; Wang et al. 2015; Tian et al. 2016). In recent years, it has observed NGC 2301 (Wang et al. 2015), NGC 188 (Chen et al. 2016), NGC 744 (Wang et al. 2018), and NGC 869 (Zhuo et al. 2021). Figure 1 [Figure 1: see original paper] presents a color image from Aladin showing the Perseus double cluster, with the two white boxes indicating the fields of view (FOV) of 50BiN for NGC 869 (right) and NGC 884 (left). The separation between the cluster centers is 27 .47, corresponding to 18.306 pc in space. Due to the limited FOV of 50BiN (20), we can observe only one cluster at a time. In our previous work (Zhuo et al. 2021), we focused on variable stars in the region around NGC 869. In the current study, we employed 50BiN to search for variable stars in NGC 884 and its surrounding region, and combined these results with our previous work on NGC 869 to conduct a comparative study of the Perseus double clusters.

2. Observations and Data Reduction

Time-series photometry of NGC 884 was obtained with 50BiN in November 2016. The telescope features two identical optical tubes mounted on either side of the polar axis (German equatorial mount), with both tubes always pointing to the same sky area during observations. Each optical system comprises a 50 cm Ritchey-Chrétien barrel with an Andor DZ936 CCD camera (2K × 2K pixels) at the Cassegrain focus. The filter wheels for both tubes contain Johnson-Cousins-Bessel UBVRI filters, enabling any color combination for observational programs. The unvignetted field of view is 20 , with a pixel scale of 0.59 pixel^{-1}. Between November 8 and November 30, 2016, we acquired a total of 17,465 CCD images, consisting of 9,247 B-band and 8,218 V-band frames. Exposure times were 30 s for B-band and 40 s for V-band. Table 1 provides the detailed observation log for NGC 884.

Following the same procedure as our previous studies (Wang et al. 2015; Zhuo et al. 2021), the raw data for NGC 884 were processed through an automated pipeline that performs standard reduction steps including dark, bias, and flat corrections, astrometric calibration, and point-source photometry. This procedure yields instrumental magnitudes for each detected star in the field. Since our primary objective was to identify variable stars using differential photometry, no standard calibration images were obtained during the observations. However, by leveraging the extensive literature on this cluster, particularly observations made in the Johnson-Cousins system, we could relatively calibrate our images using unsaturated, non-variable stars in the field to convert instrumental magnitudes to true apparent magnitudes using the following equations:

$$B = b + a_1 + a_{2X} + a_{3Y} + a_4(B - V)$$

$$V = v + b_1 + b_{2X} + b_{3Y} + b_4(B - V)$$

where B and V are the calibrated magnitudes, b and v are the instrumental magnitudes derived from our images, X and Y are the stellar positions in the images, and the coefficients a_1 through a_4 and b_1 through b_4 are determined through least-squares fitting.

3. Data Analysis

We first calculated the Stetson variability index J (Stetson 1987) for each star using the B- and V-band time-series photometric light curves, focusing particular attention on stars with $J > 0.4$ (Zhang et al. 2003). Variable star candidates were then selected through visual inspection of both B- and V-band light curves, eliminating candidates located near image edges or contaminated by nearby bright stars. This process yielded a total of 15 variable star candidates in the current dataset, designated V1 through V15. Their light curves across the nine nights are displayed in Figure 2 [Figure 2: see original paper], with blue and black points representing differential magnitudes ΔM in the B and V bands, respectively.

We cross-referenced these 15 candidates with SIMBAD using their coordinates and found that V1–V10, V12, V14, and V15 had been previously confirmed as variable stars. For comparison purposes, we include the WEBDA IDs for these known variables. Table 2 lists the basic parameters for all 15 variable stars, including J2000 coordinates, parallaxes and proper motion data from Gaia DR3 (Gaia Collaboration et al. 2023), membership probabilities derived from these parameters (see Section 3.1), and effective temperatures from Slesnick et al. (2002). The final column provides classifications based on light curve morphology, periods, and positions on the color-magnitude diagram (CMD), with detailed discussions below.

3.1 Membership Analysis

Classifying variable stars requires determining their cluster membership. Thanks to the astrometric and photometric data from Gaia DR3, we derived membership information for all stars in our time-series photometric dataset. Column 11 of Table 2 shows the membership flags.

We first used data from the cores of NGC 869 ($\alpha = 34^\circ.7408$, $\delta = 57^\circ.1339$) and NGC 884 ($\alpha = 35^\circ.5841$, $\delta = 57^\circ.1489$) within a radius of approximately 15 as samples for identifying member stars, preserving right ascension, declination, proper motion, parallax, G magnitude, and $BP - RP$ color. We then selected stars with Gmag < 18 mag based on the limiting magnitude of 50BiN and the photometric errors in Gaia DR3. As shown in Figure 3 [Figure 3: see original paper], we employed a double Gaussian approach to analyze the proper motions in right ascension (pmRA) and declination (pmDEC) for both clusters. The red line represents member stars of NGC 869, the red dotted line represents field stars of NGC 869, the blue line represents member stars of NGC 884, and the blue dotted line represents field stars of NGC 884. Working in the pmRA-pmDEC plane, we identified 1,513 member stars for NGC 869 and 1,311 for NGC 884. Applying sigma constraints to the parallaxes reduced these numbers to 1,368 and 1,154 members, respectively. To ensure reliability, we cross-checked our results with those of Currie et al. (2010), finding over 80% overlap. Ultimately, 11 of the 15 variable stars were confirmed as cluster members.

Figure 4 [Figure 4: see original paper] shows the positions of variable stars on the CMD, with different symbols indicating different types. Cyan dots represent cluster members, hollow circles represent variable stars that are cluster members, solid circles represent non-members, blue hollow circles denote Be stars, red hollow circles indicate eclipsing binaries (EBs), and orange hollow and solid circles represent variables of unknown type. The black solid line shows the Padova theoretical isochrone (Bressan et al. 2012) using cluster parameters from Currie et al. (2010).

3.2 Discovery of Two New Variable Stars

We constructed a temperature-luminosity (HR) diagram for the 15 variable stars, shown in Figure 5 [Figure 5: see original paper]. The yellow and cyan dashed lines represent the theoretical instability strips for β Cephei and slowly pulsating B (SPB) stars (Miglio et al. 2007), while the black and green dashed lines represent the instability strips for δ Scuti and γ Doradus stars (Xiong et al. 2016). The effective temperatures for stars marked with red symbols come from Slesnick et al. (2002), while those for blue triangles were calculated using empirical relationships from Torres (2010). Luminosities were obtained using the method described by Joshi et al. (2020).

The two newly discovered variable stars in this study are V11 and V13. Although they lie near the δ Scuti and γ Doradus instability strips, their non-member status precludes classification based solely on location. Nevertheless, their light curves exhibit significant photometric variations.

3.3 Be Stars

We used the Period04 toolkit (Lenz & Breger 2005) to analyze the frequency content of the variable candidates' light curves. Based on their CMD positions, periods, and light curve morphologies, we classified V1, V2, V6, V7, and V8 as Be stars (Slettebak 1985; Keller et al. 2001; Bragg & Kenyon 2002; Dimitrov et al. 2018). These are B-type stars showing one or more Balmer emission lines in their spectra (Collins 1987). For V1, we detected only a dominant frequency of f = 1.570087 day^{-1}. V6 was classified as a Be star by Bragg & Kenyon (2002) based on low-intensity emission lines in spectroscopic observations, but was later reclassified as a β Cep star by Labadie-Bartz et al. (2020) through frequency analysis of light curves of known O- and B-type stars, who obtained a primary frequency of f = 4.414700 day^{-1}.

3.4 Eclipsing Binaries

Variable stars V3, V4, and V9 are classified as eclipsing binaries (EBs). In an EB system, two stars orbit a common center of mass. Based on light curve morphology, EBs can be subdivided into EA, EB, and EW types. The International Variable Star Index (VSX) classifies V3, V4, and V9 as EA-type. EA-type systems (Algol-type) consist of two detached components. From our time-series photometric data, we calculated a period of P = 0.94378 day for V3, which confirms the VSX value of 0.94524 day and is consistent with the 0.95 day period reported by Saesen et al. (2010). For V4 and V9, our observations did not cover complete orbital cycles, though the light curve minima reveal their nature. Saesen et al. (2010) determined a period of 11.61 days for V4, which is not specified in VSX. Notably, VSX suggests a period of 2.7348 days for V9, which differs significantly from the 8.2 days reported by Saesen et al. (2010). This discrepancy warrants further investigation.

3.5 Other Variables

Among the remaining seven variable stars, V5, V11, V13, and V15 are non-member stars tentatively classified as unknown types. Saesen et al. (2010) reported a frequency of f = 8.236 day^{-1} for V5, with a follow-up study by Saesen et al. (2013) extracting nine frequencies. Our analysis yields frequencies of f = 21.195193 day^{-1} for V11, f = 15.118787 day^{-1} for V13, and f = 29.028512 day^{-1} for V15.

Variable stars V10, V12, and V14 are cluster members located near the SPB instability strips and warrant further investigation. Due to the limited duration of our data, we extracted frequencies of f_B = 5.349821 day^{-1} in the B band and f_V = 4.351627 day^{-1} in the V band for V10. These differ slightly from the two frequencies $f_1 = 2.6004$ day^{-1} and $f_2 = 5.428900$ day^{-1} reported by Saesen et al. (2013). For V12, our derived frequency of f = 3.000267 day^{-1} differs from both $f_1 = 1.99999$ day^{-1} and $f_2 = 1.858900$ day^{-1} from Saesen et al. (2013). For V14, we extracted f = 2.979968 day^{-1}, which agrees well with f = 2.974200 day^{-1} from Saesen et al. (2013).

4. Binary Content of the Double Clusters

We determined cluster member stars in Section 3.1 and subsequently calculated the binary star fraction. First, we selected stars in the CMD within the range $14 < \mathrm{Gmag} < 17$ as a subsample. We divided Gmag into 15 equal bins and identified the highest-density point in each bin to fit a curve using least squares, thereby defining the main sequence (MS) ridge line. When restricted to this subsample, the MS ridge is nearly linear. To determine the binary content, we constructed a new coordinate system using the MS ridge line as the Y-axis direction (pseudo-magnitude) and defining the axis perpendicular to the average MS ridge direction as the X-axis (pseudo-color). To define the Y-axis, we calculated the average tangents of the 15 bins and determined their angle relative to the current coordinate system. Figure 6 [Figure 6: see original paper] shows the positions of the 15 tangents for NGC 869 (left) and NGC 884 (right). We then transformed the stars in the subsample into this new coordinate system (Figure 7 [Figure 7: see original paper]). A histogram of all targets in pseudo-color was created with a bin size of 0.05 mag to calculate the binary fraction (Figure 8 [Figure 8: see original paper]).

The scatter in Figure 8 originates from two sources: photometric errors and the presence of invisible companions (binaries). In the pseudo-color-pseudo-magnitude diagram, the peak of the distribution corresponds to the MS ridge. Since no binaries exist to the left of the MS ridge, stars on the MS ridge are all single stars with random photometric errors. To the right of the MS ridge, we find both single stars with photometric errors and binary stars exhibiting such errors. We fitted the first four bins (up to the MS ridge) with a Gaussian curve and mirrored it to account for all single stars. The binary fraction was then calculated using Monte Carlo simulations to fit Gaussians for both single and binary components. The histograms of simulated single stars are shown in Figure 9 [Figure 9: see original paper] for both clusters.

Finally, we subtracted the corresponding bins in Figure 9 from those in Figure 8 for NGC 869 (left) and NGC 884 (right) to obtain the histograms shown in Figure 10 [Figure 10: see original paper]. For comparison, the blue histogram in Figure 10 shows the photometry of single stars, while the red curve represents the Gaussian fit. By calculating the area under the curve, we determined the binary fraction to be less than 0.122 for NGC 869 and less than 0.192 for NGC 884.

5. Summary and Discussion

This work represents the third paper in our series on variable stars in open clusters. We intensively observed NGC 884, one of the young open clusters in the well-known Perseus double cluster, over 14 clear nights in November 2016 using the 50BiN telescope. Johnson-Cousins B and V filters were employed, yielding more than 17,000 images in both passbands. Based on our differential photometry catalog, we searched for variable stars using the same methodology as in our previous studies of NGC 2301 (Wang et al. 2015) and NGC 869 (Zhuo et al. 2021).

The main findings of this work can be summarized as follows. First, using differential photometry techniques, we detected 15 variable stars in the field of view of NGC 884. Based on constraints from proper motion and parallax data, V1–V4, V6–V10, V12, and V14 are cluster members, while V5, V11, V13, and V15 are field stars. Second, we discovered two new variable stars, V11 and V13. Third, the light curves of V7 show features similar to eclipsing binary light curves, warranting further investigation. Fourth, the binary star fraction is less than 0.122 for NGC 869 and less than 0.192 for NGC 884. Compared to NGC 869, the companion cluster NGC 884 exhibits markedly different variable star content. Table 3 presents a comparison of variable stars between NGC 869 and NGC 884.

The double clusters are gravitationally bound and share the same physical properties, including age and metallicity, strongly suggesting a common origin and coeval dynamical evolution. The differences in variable star content, particularly in binary systems, imply that the system may have undergone dynamical interactions that have altered the stellar populations in both clusters (Bidelman 1943; Pišmiš 1953; Vogt 1971). Further studies examining the stellar components of both clusters in the context of the dynamical co-evolution of this unique double cluster system will be essential.

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