A Proper Motions Study of the Globular Cluster NGC 3201

Devesh P. Sariya\textsuperscript{1}, Ing-Guey Jiang\textsuperscript{1}, and R. K. S. Yadav\textsuperscript{2}
\textsuperscript{1} Department of Physics and Institute of Astronomy, National Tsing-Hua University, Hsin-Chu, Taiwan; deveshpath@gmail.com
\textsuperscript{2} Aryabhata Research Institute of Observational Sciences, Manora Peak, Nainital 263 002, India

Received 2016 August 29; revised 2017 January 13; accepted 2017 January 16; published 2017 February 27

Abstract

With a high value of heliocentric radial velocity, a retrograde orbit, and suspected to have an extragalactic origin, NGC 3201 is an interesting globular cluster for kinematical studies. Our purpose is to calculate the relative proper motions (PMs) and membership probability for the stars in the wide region of globular cluster NGC 3201. PM based membership probabilities are used to isolate the cluster sample from the field stars. The membership catalog will help address the question of chemical inhomogeneity in the cluster. Archive CCD data taken with a wide-field imager (WFI) mounted on the ESO 2.2 m telescope are reduced using the high-precision astrometric software developed by Anderson et al. for the WFI images. The epoch gap between the two observational runs is $\sim 14.3$ years. To standardize the $BVI$ photometry, Stetson’s secondary standard stars are used. The CCD data with an epoch gap of $\sim 14.3$ years enables us to decontaminate the cluster stars from field stars efficiently. The median precision of PMs is better than $\sim 0.8$ mas yr$^{-1}$ for stars having $V < 18$ mag that increases up to $\sim 1.5$ mas yr$^{-1}$ for stars with $18 < V < 20$ mag. Kinematic membership probabilities are calculated using PMs for stars brighter than $V \sim 20$ mag. An electronic catalog of positions, relative PMs, $BVI$ magnitudes, and membership probabilities in the $\sim 19.7 \times 17$ arcmin$^2$ region of NGC 3201 is presented. We use our membership catalog to identify probable cluster members among the known variables and X-ray sources in the direction of NGC 3201.

Key words: astrometry – catalogs – globular clusters: individual (NGC 3201)

Supporting material: machine-readable table

1. Introduction

Galactic globular clusters are very important for the study of the halo and bulge regions of our Galaxy. In particular, they are the best tools for understanding the kinematics and dynamics of the halo region of the Milky Way by the virtue of being easily distinguishable at large distances (Cudworth 1997; Dambis 2006). Since the emergence of CCDs, proper motion (PM) studies can be carried out with unprecedented precision using CCD data with smaller epoch differences than data from photographic plates. PMs are the root to learn about the kinematics and orbit of the clusters, as well as providing kinematical membership probabilities of the stars. Membership status is often pivotal to spectroscopic studies, to avoid observing field stars lying in the cluster’s field (Cudworth 1986). At fainter magnitudes, in particular, field stars dominate, and PMs become very important in removing them from the sample (Piotti et al. 2004).

NGC 3201 is a sparse, metal-poor, intermediate-mass halo globular cluster. The basic cluster parameters of NGC 3201 taken from Harris (1996, 2010 edition) are listed in Table 1. Since the cluster is less centrally concentrated than most other globular clusters, even ground based telescopes can probe its central region. Due to this advantage and its proximity, NGC 3201 has been studied extensively for photometric studies (Menzies 1967; Alcaino 1976; Lee 1977; Alcaino & Liller 1981; Alcaino et al. 1989; Cacciari 1984a, 1984b; Penny 1984; Brewer et al. 1993; Covino & Ortolani 1997; Kravtsov et al. 2009 etc.). von Braun & Mateo (2001) presented an extinction map for NGC 3201 and explained that due to its low Galactic latitude, the effect of differential reddening across this globular cluster is very significant. NGC 3201 has been studied for the question of chemical abundances and possibility of inhomogeneity in its stellar population by several authors (e.g., Chun 1988; Gonzalez & Wallerstein 1998; Covey et al. 2003; Kravtsov et al. 2010; Muñoz et al. 2013; Simmerer et al. 2013; Mucciarelli et al. 2015 and references therein). NGC 3201 is known to harbor many variable stars including RR Lyrae, SX Phoenicis, and so on. It belongs to Oosterhoff type I according to the Oosterhoff dichotomy of RR Lyrae stars. The cluster has been the subject of many investigations for searching and characterizing its variable stars (e.g., Lee & Carney 1999; Piersimoni et al. 2002; von Braun & Mateo 2002; Layden & Sarajedini 2003; Mazur et al. 2003; Arellano Ferro et al. 2014; Kaluzny et al. 2016 and references therein). Webb et al. (2006) studied NGC 3201 using the XMM—Newton X-ray observatory.

NGC 3201 is a very interesting globular cluster for its kinematical features. It shows a very high value of heliocentric radial velocity (494.2 km s$^{-1}$; Cote et al. 1994), suggesting a retrograde orbit about the Galactic center (Casetti-Dinescu et al. 2007). It has been suspected to have an extragalactic origin and has probably been accreted by the Milky Way. Dynamics of the cluster was studied by Da Costa et al. (1993) and Cote et al. (1994, 1995). The Radial Velocity Experiment (RAVE) catalog was used to study this cluster by Kunder et al. (2014) and Anguiano et al. (2015, 2016). Anguiano et al. (2016) presented the distribution of stars based on UCAC4 PMs. Chen & Chen (2010) state that NGC 3201 appears to have passed through the Galactic disk a few Myr ago and the cluster has clumps along its Galactic north–south axis.

Casetti-Dinescu et al. (2007) provided the absolute PM of NGC 3201 ($\mu_l, \cos \delta = 5.28 \pm 0.32$ mas yr$^{-1}$, $\mu_b = -0.98 \pm 0.33$ mas yr$^{-1}$), using a combination of photographic plate data with CCD. Recently Zloczewski et al. (2012, hereafter Z12)
have determined PMs for the stars in the region of NGC 3201 and provided membership probabilities in the central region of the cluster.

From the previous discussion, it is noticeable that this kinematically interesting globular cluster is not well studied for PMs over a wider region. As reported by Brewer et al. (1993) and Kravtsov et al. (2009), the studies of NGC 3201 are obstructed by significant field star contamination. Wide field imagers (WFIs) enable us to cover the broad regions of star clusters, sometimes up to their tidal trails. The archive data observed with WFI@2.2 m at La Silla, Chile, has been used previously to provide PMs using a time gap of a few years (Anderson et al. 2006; Yadav et al. 2008, 2013; Bellini et al. 2009; Sariya et al. 2012; Sariya & Yadav 2015). NGC 3201, being a sparse cluster, and the available epoch gap being \( \sim 14.3 \) years in the archive data of WFI@2.2M allows us to determine precise PMs over a broad region of the cluster.

The main goal of the present article is to provide relative PMs and membership probabilities \((P_m)\) for stars having visual magnitudes up to 20 mag in the wide field of NGC 3201. We also provide an electronic catalog for 8322 stars that contains \(B, V, I\) magnitudes, PMs, and membership probabilities for the follow-up studies of the cluster. Our membership catalog covers a region of \( \sim 19.7 \times 17 \text{ arcmin}^2 \), which is wider than the area covered in the PM study by Zi12 (\( \sim 14.6 \times 9.7 \text{ arcmin}^2 \)). Our membership catalog will be helpful in selecting the more likely cluster members while addressing the question of chemical inhomogeneity, which has been an intriguing aspect of this cluster.

Information about the data used and reduction procedures are described in Section 2, where we also discuss PMs and vector-point diagrams (VPDs), with color–magnitude diagrams (CMDs) of the cluster. Cluster membership analysis is provided in Section 3. We use our membership catalog to examine the membership status of earlier reported variables and X-ray sources in Section 4. The electronic catalog being presented for the further study of the cluster is explained in Section 5. Conclusions follow in Section 6.

### 2. Data Used and Reduction Procedures

To determine the PMs of the stars in this work, we used archive images\(^3\) from observations made with the 2.2 m ESO/MPI telescope at La Silla, Chile. This telescope contains a mosaic camera called the WFI, consisting of \(4 \times 2\) (i.e., 8 CCD chips). Since each CCD has an array of \(2048 \times 4096\) pixels, WFI ultimately produces images with a \(34 \times 33 \text{ arcmin}^2\) field of view.

Table 2 presents the details of the observational log of the archive data. The observational run of the first epoch contains two images in \(B, V\) and \(I\) bands, each with \(240\) s exposure time observed on 1999 December 05. In the second epoch, we have 35 images with \(40\) s exposure time each in \(V\) filter observed during the period of 2014 April 02–05. Thus the epoch gap between the data is \(\sim 14.3\) years. As can be seen in the Table 2, seeing in the images used are \(0.8-1.1\) arcsec, and airmass values lie between \(\sim 1.1\) and \(1.3\).

#### Table 2

| Filters | Exposure Time (s) | Seeing (arcsec) | Airmass |
|---------|-------------------|-----------------|---------|
|         | 1999 Dec 05 (First epoch) | 1.1 |
|         | 2014 Apr 02–05 (Second epoch) | 1.1 |

To derive PMs from the WFI@2.2 m mosaic CCD images, we used the astrometric procedure developed by Anderson et al. (2006, hereafter A06). The technique involves the usual initial steps of de-biasing and flat-fielding. One of the decisive factors in providing precise positions of the stars is constructing a good point spread function (PSF) for the WFI images. Since the shape of the PSF changes across the mosaic CCD, we capture this variability by using an array of 15 PSFs per CCD chip (3 across and 5 high), as explained in A06. To furnish positions and fluxes of the objects in an image, an array of empirical PSFs are constructed. These PSFs are saved in a look-up table on a very fine grid of a quarter pixel size. Each PSF goes out to a radius of 25 pixels, and each pixel is split in 4 equal parts, thus giving \((201, 201)\) grid points for a PSF. The center of the PSF is located at the central gridpoint (101, 101). A06 presented the automated code we are now using to iteratively determine the precise positions and instrumental magnitudes for the brightest down to faintest stars for \(B, V, I\) bands.

As documented in A06, WFI@2.2 m is affected by significant geometric distortion in the focal plane, which leads the pixel scale across the field-of-view to change effectively. The corrections to account for the geometric distortion were derived using dithered observations of Baade’s window, which lies in the Galactic bulge (see A06). The corrections have been noted in a look-up table comprising \(9 \times 17\) elements for each chip. For any particular location, a bi-linear interpolation between the four closest grid points from the look-up table to the target point delivers the distortion correction. Still, the distortion may vary over time for the WFI, and is typically larger near the edges of the image. These factors lead to uncertainty in distortion corrections. To tackle this uncertainty, we followed the local transformation approach as described in

---

\(^3\) http://archive.eso.org/eso/eso_archive_main.html
Section 7 of the article A06. According to the local transformation approach, transformations from one frame to another are obtained locally (i.e., with respect to some stars in our own images). Because cluster stars exhibit a lesser amount of internal dispersion than the field stars, cluster stars are chosen based on their location in CMD and motion are chosen for reference. Initially we choose stars lying on the main sequence, sub giant and red giant branches by making blue and red envelope for the sequences in the CMD. In subsequent attempts, the selection is done using PMs. The process is iterated multiple times to provide the best possible results. After positions of stars are determined in all frames, we use six-parameter linear transformations to transform the positions from one frame to another. This approach resembles the classical “plate-pair” method (e.g., Sanders 1971a; Tian et al. 1998), but it is more generalized and can be used for all possible combinations of the first and second epoch frames. The relative PM of a target star will be the average of all displacements for inter-epoch transformations. Since PMs do not contribute to the intra-epoch displacements, they are used to calculate errors in PM measurements.

2.1.1. Calibrating the Photometry

Instrumental $B$, $V$, and $I$ magnitudes were transformed into the standard Johnson–Cousin system using secondary standard stars provided by P. Stetson.4 The standard stars used for calibration have a brightness range of $12.6 \leq V \leq 19.8$ and color ranges of $0.4 \leq (B - V) \leq 1.5$ and $0.4 \leq (V - I) \leq 1.9$. A total of 160 stars for $BV$ magnitudes and 165 stars for $I$ magnitudes were used in the calibration process.

We used the transformation equations written as follows to derive the photometric zero points and color terms:

$$B_{\text{std}} = B_{\text{ins}} + C_b \times (B_{\text{ins}} - V_{\text{ins}}) + Z_b$$
$$V_{\text{std}} = V_{\text{ins}} + C_v \times (V_{\text{ins}} - V_{\text{ins}}) + Z_v$$
$$I_{\text{std}} = I_{\text{ins}} + C_i \times (I_{\text{ins}} - I_{\text{ins}}) + Z_i$$

where instrumental magnitudes and standard secondary magnitudes have been denoted by subscripts “ins” and “std,” respectively. $C_b$, $C_v$, and $C_i$ denote the color terms, while $Z_b$, $Z_v$, and $Z_i$ are the global zero-points. As a result of the calibration, the values of the color terms are $0.39$, $-0.07$, and $0.12$, whereas the zero-points are $24.79$, $24.18$, $23.27$ for $B$, $V$, and $I$ filters, respectively. These values of color terms and zero point agree with the values posted on the WFI@2.2 m webpage.5

The photometric standard deviations for individual photometric bands were calculated by reducing multiple observations to a common reference frame. Figure 1 presents the rms error in the magnitudes for $B$, $V$, and $I$ magnitudes as a function of visual magnitude. The values of average rms are less than $\sim 0.01$ mag for stars brighter than $19$ mag for $B$ and $I$ filters, and better than $\sim 0.01$ mag for $V < 20$ mag.

2.1.2. Calibrating the Positions

As a part of the astrometric studies of NGC 3201, we present the equatorial coordinates of stars in the International Celestial Reference System (ICRS). We used the geometric distortion correction from the look-up table given in A06 to correct the pixel coordinates $X$, $Y$ of each star in each frame, and averaged by means of a six-parameter linear transformation into a common reference frame. The online digitized sky ESO catalog in the SKYCAT software is then used to transform the averaged $X$, $Y$ positions to right ascension (R.A.) and declination (decl.) in J2000.0 equinox using IRAF6 tasks CCMAP and CCTTRAN. The transformations have rms values of about $\sim 20$ mas. The relatively high accuracy of our distortion corrections as well as the reasonable stability of the intra-chip positions make it possible to apply a single plate model that includes linear and quadratic terms and a small but significant cubic term in each coordinate. In addition, this solution removes the effects caused by differential refraction.

2.2. Proper Motion Determinations

We used 6 images from the first epoch and 35 images from the second epoch to determine PMs for NGC 3201 stars. Having a large number of images minimizes the value of the standard error in the PMs.

We started with a selection of photometric clusters members (i.e., members selected on the basis of their position in $V$ versus $(B - V)$ CMD). We selected stars lying near the cluster sequences in the CMD, with brightness in the range of $14 \leq V \leq 19$. These are used as a local reference to transform the coordinates of the stars between the epochs. Adopting only those stars lying on the cluster sequences in the CMD and having PM errors $< 1.0$ mas yr$^{-1}$ ensures that the PMs are determined with respect to the systematic motion of the cluster. To minimize the influence of uncorrected geometric distortion residuals, a local transformation based on the closest 25

---

4 http://www3.cadc-ccda.hia-iha.nrc-cnrc.gc.ca/community/STETSON/standards/
5 http://www.ls.eso.org/lasilla/sciops/2p2/E2p2M/WFI/zeropoints/
6 IRAF is distributed by the National Optical Astronomical Observatory, which is operated by the Association of Universities for Research in Astronomy, under contact with the National Science Foundation.
reference stars on the same CCD chip was used. We did not find any systematics larger than random errors close to the corners or edges of the CCD chips.

The routine described in A06 has an iterative nature, and we iterated it to remove some stars from the initial photometric member list. Stars were eliminated if they had PMs inconsistent with cluster membership, in spite of their colors placing them near the cluster sequence in the CMD. PMs and their rms errors are plotted as a function of visual magnitude in Figure 2. The median value of PM error is ~0.8 mas yr^{-1} for stars brighter than V ~ 18 mag, which increases up to ~1.5 mas yr^{-1} for stars in the magnitude range of 18 < V < 20 mag.

2.2.1. Cluster CMD Decontamination

One of the main reasons to carry out PM analysis for star clusters is to isolate the cluster sample from the field stars and to produce a CMD with only the most probable cluster members. Figure 3 clearly demonstrates the strength of PM analysis in separating the field stars using VPDs in the top panels, in combination with V versus (B - V) CMDs in the bottom panels. In the left panels of the figure, the entire sample of stars is shown, while the middle panels and right panels represent likely cluster members and field stars, respectively. In the top middle panel, VPD has a circle of radius ~5 mas yr^{-1} around the cluster centroid. This motion circle is our provisional criterion for assigning membership to the stars, before membership probabilities are determined. The radius of the circle is chosen as a compromise between losing cluster members with poorly measured PMs and including some field stars that have their PMs consistent with the cluster’s mean PM. The shape of the cluster members’ PM distribution in the VPD is round, which suggests that our PM measurements are not affected by any systematics. It is pretty obvious from the figure that having a large epoch gap for CCD data has produced a CMD almost free from field stars.

Figure 4 shows the (B - V), V CMD, which is binned along the magnitude axis. To identify provisional cluster members, different selection criteria were used in different magnitude bins. The criterion was tighter for bright stars, as they have more reliable measurements, but is less stringent for fainter stars. As can be seen in Figure 4, fainter stars have poorer PM determinations compared to brighter stars: PM uncertainty increases from 1.2 to 2.5 mas yr^{-1} from the brightest bin to the faintest one. We therefore adopt a PM selection radius that increases from 2.5 mas yr^{-1} in the brightest magnitude bin to 6.0 mas yr^{-1} in the faintest one. However, we still have a good enough decontamination of field stars even in the fainter magnitudes.

3. Membership Probabilities

In Figure 3, two different groups of stars are distinguishable based on their motion, although a larger fraction of the stars are inside the circle for provisional cluster membership. The next step is to determine membership probabilities of stars, which will yield a quantitative significant number for a particular star belonging to the cluster. The credit to set up a mathematical model to use PMs to determine membership probabilities goes to Vasilevskis et al. (1958). The maximum likelihood principle to compute membership probabilities was introduced by Sanders (1971b). Over the years, methods to calculate membership probabilities have been refined (e.g., Stetson 1980; Zhao & He 1990; Zhao & Shao 1994). In this study, we use the method given by Balaguer-Núñez et al. (1998). This method has been previously used for both globular clusters (Bellini et al. 2009; Sariya et al. 2012; Sariya & Yadav 2015) and open clusters (Yadav et al. 2013). According to this method, two frequency distribution functions are constructed for a particular ith star. Frequency distributions of cluster stars (\(\phi_c^i\)) and field stars (\(\phi_f^i\)) are presented by the equations given here:

\[
\phi_c^i = \frac{1}{2\pi \sqrt{(\sigma_x^2 + \epsilon_x^2)(\sigma_y^2 + \epsilon_y^2)}} \times \exp\left\{ -\frac{1}{2} \left[ \frac{(\mu_x - \mu_x)^2}{\sigma_x^2 + \epsilon_x^2} + \frac{(\mu_y - \mu_y)^2}{\sigma_y^2 + \epsilon_y^2} \right]\right\}
\]

and

\[
\phi_f^i = \frac{1}{2\pi (1 - \gamma^2) \sqrt{(\sigma_x^2 + \epsilon_x^2)(\sigma_y^2 + \epsilon_y^2)}} \times \exp\left\{ -\frac{1}{2(1 - \gamma^2)} \left[ \frac{(\mu_x - \mu_x)^2}{\sigma_x^2 + \epsilon_x^2} + \frac{(\mu_y - \mu_y)^2}{\sigma_y^2 + \epsilon_y^2} \right]\right\}
\]

\[
- \frac{2\gamma(\mu_x - \mu_x)(\mu_y - \mu_y)}{\sqrt{(\sigma_x^2 + \epsilon_x^2)(\sigma_y^2 + \epsilon_y^2)}} + \frac{(\mu_x - \mu_x)^2}{\sigma_x^2 + \epsilon_x^2} + \frac{(\mu_y - \mu_y)^2}{\sigma_y^2 + \epsilon_y^2}
\]

where (\(\mu_{x i}, \mu_{yi}\)) are the PMs of ith star, while (\(\epsilon_{xi}, \epsilon_{yi}\)) are the PM errors. (\(\mu_{xc}, \mu_{yc}\)) represent the cluster’s PM center and (\(\mu_{xf}, \mu_{yf}\)) are the field PM center. For the cluster members, the intrinsic PM dispersion is denoted by \(\sigma_x\), whereas \(\sigma_{xf}\) and \(\sigma_{xf}\) exhibit the field intrinsic PM dispersions. The correlation coefficient \(\gamma\) is calculated as

\[
\gamma = \frac{(\mu_x - \mu_x)(\mu_y - \mu_y)}{\sigma_x \sigma_y}
\]
The spatial distribution of the stars was not considered in calculating membership. In computing $f_{nc}$ and $f_{nf}$, we used those stars that have PM errors better than $\sim 2$ mas yr$^{-1}$. In VPD, the center of the cluster stars is found to be $(\mu_x, \mu_y) = (0, 0)$ mas yr$^{-1}$. The intrinsic PM dispersion for the cluster stars ($\sigma_c$) could not be ascertained reliably using our PM data. Pryor & Meylan (1993) list the value of radial velocity dispersion for NGC 3201 as 5.2 km s$^{-1}$. Considering the value of the distance of NGC 3201 as 4.9 kpc (Harris 1996, 2010 edition), the internal PM dispersion becomes $\sim 0.22$ mas yr$^{-1}$. Hence, we used $\sigma_c = 0.22$ mas yr$^{-1}$. For field stars, we have $(\mu_x, \mu_y) = (13.8, 4.8)$ mas yr$^{-1}$ and $(\sigma_x, \sigma_y) = (2.5, 2.1)$ mas yr$^{-1}$.

If $n_c$ and $n_f$ are the normalized number of cluster and field stars, respectively (i.e., $n_c + n_f = 1$), the total distribution function can be calculated as

$$\phi = (n_c \times \phi^c) + (n_f \times \phi^f).$$

As a result, the membership probability for the $i$th star is given by

$$P_\mu(i) = \frac{\phi^c(i)}{\phi(i)}.$$

In Figure 5, membership probabilities are shown as a function of visual magnitude. The figure shows clear separation of cluster and field stars as sharp distributions of stars around membership values $P_\mu \sim 100\%$ and $P_\mu \sim 0\%$. However, due to increasing errors at fainter regime, one can notice a number of stars with intermediate values of $P_\mu$, for magnitudes fainter than

---

**Figure 3.** (Top panels) Proper motion vector-point diagrams (VPDs). Zero point in VPD is the average motion of the assumed cluster stars. (Bottom panels) $V$ vs. $(B-V)$ CMDs. (Left) The whole sample. (Center) Stars in VPD within $\sim 5$ mas yr$^{-1}$ around the cluster mean motion. (Right) Probable field stars in the region of NGC 3201. For all the plots, only stars having PM error better than 2 mas yr$^{-1}$ in each coordinate have been considered.
The histogram of membership probabilities for 8322 stars is shown in Figure 6. The presence of higher peaks for the leftmost and rightmost bins suggest that the method used for the membership determination is effective for NGC 3201. We find 5981 stars that have membership probabilities larger than 80%. The spatial distribution of the stars is shown in Figure 7. To distinguish between the cluster members and field stars, we have used different symbols for stars having $m_P > 80\%$, $10\% < m_P \leq 80\%$, and $m_P \leq 10\%$. The cutoff values of $m_P$ are based on the histogram shown in Figure 6.

Figure 8 presents the CMD of stars having $m_P > 80\%$. In this CMD, cluster sequences for stars brighter than $V \sim 20$ mag can be seen. In addition, this CMD shows stars of various evolutionary stages like sub-giants, red giants, horizontal branch stars, and blue stragglers. All the cluster sequences in this CMD look cleaner with minimal field contamination.
mentioned earlier, NGC 3201 shows differential reddening, due to which the cluster sequences are broadened in CMD. As discussed by Kravtsov et al. (2009), the red giant branch of the cluster, in particular, shows significant broadening. In addition to this, we find gaps in the red giant branch at $V \sim 13$ and $V \sim 15$, the former one being more significant. These gaps have been reported by Lee (1977) in his photometric study of NGC 3201. The horizontal branch of NGC 3201 is well developed and extended, with a relatively unclear instability strip.

3.1. Comparison with Z112

The PMs presented in this study were compared with the catalog given by Z112. For comparison, we plotted the spatial distributions of our catalog with Z112 in Figure 9. In this figure, our catalog stars are shown with red filled circles, while Z112 stars are shown with blue triangles. It is clearly seen in the figure that the present investigation extends the PM studies of NGC 3201 to a wider region. In the additional observed area in
our catalog, we have PM information from about 2000 stars. For the common stars, the differences in both PM components between the two catalogs are shown in Figure 10. Values of the 3σ-clipped median of the PM differences are $(\mu = 0.04 \pm 0.54)$ mas yr$^{-1}$ and $(\mu = 0.05 \pm 0.62)$ mas yr$^{-1}$. Our PMs exhibit consistency with the Z112 data for $V < 20$ mag.

4. Membership of Variables and X-Ray Sources

We used the membership catalog to ascertain the membership status of the reported variable stars and X-ray sources in the region of NGC 3201. The details of the comparison are listed in Table 3. The variable stars of NGC 3201 have been compiled on Clement’s webpage of the catalog of variable stars in globular clusters. Recently some new variables were detected by Kaluzny et al. (2016). We found four variable stars in common with our catalog. In Table 3, V137 comes from the variables listed in Kaluzny et al. (2016), and the coordinates of the other three variables have been taken from Clement’s webpage. As can be seen in Table 3, variables V92 and V98 have a 100% probability of being cluster stars. The two other variable stars, V71 and V137, have $P_{m} \sim 0\%$, which implies that they are not cluster members. The X-ray sources in the NGC 3201 field-of-view have been identified by Webb et al. (2006). Out of 10 X-ray sources found, five sources (ID$^{X} = 22, 26, 45, 58, 59$) have a membership probability close to 100%, which makes them very probable X-ray cluster members. Another X-ray source, ID$^{X} = 48$, should also be a probable cluster member based on its membership probability. ID$^{X} = 25, 30, 33, 46$ have $P_{m} \sim 0\%$, which means they do not belong to NGC 3201. Figure 11 shows the CMD of all the stars listed in our membership catalog, with the variables and X-ray sources shown with different symbols.

5. The Catalog

The electronic catalog from the present study contains relative PMs, PM errors, membership probabilities, and photometric magnitudes in $B, V, I$ bands with rms errors for 8322 stars in the direction of NGC 3201. Column (1) of the catalog gives the running number; columns (2) and (3) present the J2000.0 equatorial coordinates, while columns (4) and (5) show positions of the stars ($X$ and $Y$) in CCD pixels. Relative PMs and PM errors are listed in columns (6)–(9). Columns (10)–(15) provide photometric $B, V, I$ magnitudes and their rms errors. The final column, column (16), represents the membership probability $P_{m}$. Some initial lines from the electronic catalog are shown in Table 4.
Table 4
The Membership Catalog for NGC 3201 (Initial Few Lines)

| ID     | $\alpha_{2000}$ | $\delta_{2000}$ | $X$ (pixel) | $Y$ (pixel) | $\mu_x \cos(\delta)$ (mas yr$^{-1}$) | $\mu_y$ (mas yr$^{-1}$) | $\sigma_{\mu_x}$ (mas yr$^{-1}$) | $\sigma_{\mu_y}$ (mas yr$^{-1}$) | $B$ (mag) | $V$ (mag) | $I$ (mag) | $\sigma_I$ (mag) | $P_e$ (%) |
|--------|-----------------|-----------------|-------------|-------------|--------------------------------------|-------------------------|-----------------------------------|-----------------------------------|-----------|-----------|-----------|-------------------|----------|
| 1      | 10:17:43.87     | -46:36:49.1     | 2535.4886   | 247.4757    | 10.9367                             | 0.7142                  | 2.9779                            | 0.3006                            | 17.4382   | 0.0044    | 16.6389   | 0.0045            | 0        |
| 2      | 10:17:17.45     | -46:36:50.5     | 3681.3510   | 247.7929    | -0.6062                             | 1.0181                  | 1.4117                            | 0.1478                            | 18.8624   | 0.0022    | 18.1265   | 0.0017            | 17.2219  |
| 3      | 10:16:34.53     | -46:36:49.9     | 4675.0902   | 254.5138    | 14.3016                             | 0.8902                  | 0.8736                            | 1.3054                            | 17.4766   | 0.0028    | 16.5418   | 0.0061            | 15.4859  |
| 4      | 10:17:27.99     | -46:36:46.7     | 3224.0258   | 261.3223    | 13.9711                             | 0.8437                  | 6.6451                            | 1.6193                            | 19.7695   | 0.0055    | 18.7313   | 0.0111            | 17.6100  |
| 5      | 10:17:06.37     | -46:36:44.3     | 4616.2320   | 275.8470    | 14.7467                             | 0.6278                  | 9.3091                            | 0.4916                            | 17.9729   | 0.0044    | 16.8013   | 0.0039            | 15.4686  |
| 6      | 10:16:55.80     | -46:36:44.2     | 4619.5001   | 278.2980    | 10.9301                             | 0.8520                  | 4.0641                            | 1.6559                            | 20.1599   | 0.0077    | 19.1355   | 0.0094            | 17.9470  |
| 7      | 10:17:43.89     | -46:36:41.3     | 2534.5683   | 279.9379    | -0.9899                             | 1.1377                  | 2.5727                            | 0.9101                            | 19.7977   | 0.0104    | 18.9841   | 0.0012            | 18.0374  |
| 8      | 10:17:41.74     | -46:36:37.4     | 2627.5263   | 297.0895    | 13.4994                             | 1.0762                  | 5.7681                            | 1.3270                            | 19.7509   | 0.0060    | 18.6114   | 0.0076            | 17.3379  |
| 9      | 10:17:49.71     | -46:36:36.2     | 2281.8995   | 299.8237    | 13.6555                             | 1.1161                  | 1.7871                            | 1.8352                            | 19.1304   | 0.0055    | 18.0739   | 0.0017            | 16.9377  |
| 10     | 10:17:22.46     | -46:36:31.1     | 3463.3688   | 328.1909    | 13.0958                             | 0.5066                  | 5.6286                            | 0.2441                            | 18.3758   | 0.0104    | 17.3988   | 0.0039            | 16.3546  |
| 11     | 10:17:28.71     | -46:36:29.1     | 3192.3215   | 335.1330    | 10.8703                             | 1.1676                  | 6.7231                            | 1.3137                            | 18.7126   | 0.0077    | 17.8893   | 0.0138            | 16.9378  |

(This table is available in its entirety in machine-readable form.)
6. Conclusions

We provide PMs and membership probabilities for 8322 stars in the field of globular cluster NGC 3201. Our PMs successfully separate field stars from cluster members, and we present a CMD that shows cluster sequences almost free from field stars. An electronic catalog with equatorial coordinates, PMs, membership probability, and BV I photometry is being made available to the astronomical community. The membership catalog has been used to define the membership status of variable stars and X-ray sources earlier reported in the cluster’s direction. This work also demonstrates that CCD data with only few years epoch gap can provide PMs accurate enough for the kinematic separation of cluster members.

We are indebted to an anonymous referee for a careful reading of the manuscript and giving very useful suggestions that greatly improved this article, including its language and presentation. Devesh P. Sariya and Ing-Guey Jiang acknowledge the grant from the Ministry of Science and Technology (MOST), Taiwan. The grant numbers are MOST 103-2112-M-007-007-M-007-038, and MOST 105-2811-M-007-020-M-007-024, and MOST 105-2811-M-007-024. This research used the facilities of the Canadian Astronomy Data Centre operated by the National Research Council of Canada with the support of the Canadian Space Agency. We have also used the catalog of variable stars managed by Prof. Christine Clement from University of Toronto, Canada.

References

Alcaino, G. 1976, A&A, 26, 251
Alcaino, G., & Liller, W. 1981, AJ, 86, 1480
Alcaino, G., Liller, W., & Alvarado, F. 1989, A&A, 216, 68
Anderson, J., Bedin, L. R., Piotto, G., Yadav, R. K. S., & Bellini, A. 2006, A&A, 454, 1029
Anguiano, B., De Silva, G. M., Freeman, K., et al. 2016, MNRAS, 457, 2078
Anguiano, B., Zucker, D. B., Scholz, R.-D., et al. 2015, MNRAS, 451, 1229
Arellano Ferro, A., Alcaino, G., Marconi, G., & Alvarado, F. 2009, A&A, 512, L6
Kaluzny, J., Rozyczka, M., Thompson, I. B., et al. 2016, AcA, 62, 357
Brewer, J. P., Fahlman, G. G., Richer, H. B., et al. 1993, AJ, 105, 2158
Cacciari, C. 1984a, AJ, 89, 231
Cacciari, C. 1984b, AJ, 89, 1082
Casetti-Dinescu, D. I., Girard, T. M., Herrera, D., et al. 2007, AJ, 134, 195
Chen, C. W., & Chen, W. P. 2010, ApJ, 721, 1790
Chun, M.-S. 1988, JKAS, 21, 67
Cote, P., Welch, D. L., Fischer, P., & Gebhardt, K. 1995, ApJ, 454, 788
Covey, K. R., Wallerstein, G., Gonzalez, G., Vanture, A. D., & Suntzeff, N. B. 2003, PASP, 115, 819
Covino, S., & Ortolani, S. 1997, A&A, 318, 40
Cudworth, K. M. 1986, in IAU Symp. 109, Astrometry of Star Clusters, ed. H. K. Eichhorn & R. J. Leacock (Dordrecht: Reidel), 201
Cudworth, K. M. 1997, in ASP Conf. Ser. 127, Proper Motions and Galactic Astronomy, ed. R. M. Humphreys (San Francisco, CA: ASP), 91
Da Costa, G. S., Tamblyn, P., Seitzer, P., et al. 1993, in ASP Conf. Ser. 50, Structure and Dynamics of Globular Clusters, ed. S. G. Djorgovski & G. Meylan (San Francisco, CA: ASP), 81
Dambis, A. K. 2006, A&AT, 25, 185
Gonzalez, G., & Wallerstein, G. 1998, AJ, 116, 765
Harris, W. E. 1996, AJ, 112, 1487
Kaluzny, J., Rozyczka, M., Thompson, I. B., et al. 2016, AcA, 62, 357
Lee, J.-W., & Carney, B. W. 1999, AJ, 118, 1373
Lee, S.-W. 1977, A&A, 63, 409
Mazur, B., Krzeminski, W., & Thompson, I. B. 2003, MNRAS, 340, 1205
Menzies, J. 1967, PhD thesis, Australian National Univ.
Mucciarelli, A., Lapenna, E., Massari, D., Ferraro, F. R., & Lanzioli, B. 2015, ApJ, 801, 69
Muñoz, C. J., Geisler, D., & Villanova, S. 2013, MNRAS, 433, 2006
Penny, A. J. 1984, in IAU Symp. 105, Observational Tests of the Stellar Evolution Theory, ed. A. Maeder & A. Renzini (Dordrecht: Reidel), 157
Piersimoni, A. M., Bono, G., & Ripepi, V. 2002, A&AS, 131, 89
Piotto, G., Bedin, L. R., Cassisi, S., et al. 2004, MSAIS, 5, 71
Pryor, C., & Meylan, G. 1993, in ASP Conf. Ser. 50, Structure and Dynamics of Globular Clusters, ed. S. G. Djorgovski & G. Meylan (San Francisco, CA: ASP), 357
Sanders, W. L. 1971a, A&A, 15, 368
Sanders, W. L. 1971b, A&A, 14, 226
Sariya, D. P., & Yadav, R. K. S. 2013, A&A, 584, A59
Sariya, D. P., Yadav, R. K. S., & Bellini, A. 2012, A&A, 543, A87
Simmerer, J., Ivans, I. I., Filler, D., et al. 2013, ApJL, 764, L7
Stetson, P. B. 1980, AJ, 85, 387
Tian, K.-P., Zhao, J.-L., Shao, Z.-Y., & Stetson, P. B. 1998, A&AS, 131, 89
Vasilevskis, S., Klemola, A., & Preston, G. 1958, AJ, 63, 387
von Braun, K., & Mateo, M. 2001, AJ, 121, 1522
von Braun, K., & Mateo, M. 2002, AJ, 123, 279
Webb, N. A., Wheatley, P. J., & Barret, D. 2006, A&A, 445, 155
Yadav, R. K. S., Bedin, L. R., Piotto, G., et al. 2008, A&A, 484, 609
Yadav, R. K. S., Sariya, D. P., & Sagar, R. 2013, MNRAS, 430, 3350
Zhao, J. L., & Sariya, D. P., & Sagar, R. 2013, MNRAS, 430, 3350
Zhao, J. L., & Shao, Z. Y. 1994, A&A, 288, 89
Zloczewski, K., Kaluzny, J., Rozyczka, M., Krzeminski, W., & Mazur, B. 2012, A&A, 62, 357

Sariya, Jiang, & Yadav

The Astronomical Journal, 153:134 (10pp), 2017 March