TIME-SERIES $BV$ I PHOTOMETRY FOR THE GLOBULAR CLUSTER NGC 6981$^*$. $^1$. $^4$

P. AMIGO$^1$. $^2$. $^3$. P. B. STETSON$^4$. M. CATELAN$^1$. $^2$. M. ZOCCALI$^1$. $^2$. AND H. A. SMITH$^5$

$^1$ Pontificia Universidad Católica de Chile, Instituto de Astrofísica, Av. Vicuña Mackenna 4860, 782-0436 Macul, Santiago, Chile; mcatalan@astro.puc.cl, mzoccali@astro.puc.cl
$^2$ The Milky Way Millennium Nucleus, Av. Vicuña Mackenna 4860, 782-0436 Macul, Santiago, Chile
$^3$ Universidad de Valparaíso, Departamento de Física y Astronomía, Gran Bretaña 1111, Playa Ancha, Valparaíso, Chile; pia.amigo@dfa.uv.cl
$^4$ Dominion Astrophysical Observatory, Herzberg Institute of Astrophysics, National Research Council, 5071 West Saanich Road, Victoria, BC V9E 2E7, Canada; Peter.Stetson@nrc-cnrc.gc.ca
$^5$ Department of Physics and Astronomy, Michigan State University, East Lansing, MI 48824, USA; smith@pa.msu.edu

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ABSTRACT

We present new $BV$ I photometry of the globular cluster NGC 6981, based mostly on ground-based CCD archival images. We present a new color–magnitude diagram (CMD) that reaches almost four magnitudes below the turn-off level. We performed new derivations of metallicity and morphological parameters of the evolved sequences, in good agreement with the results of previous authors, and obtain a value of $[\text{Fe}/\text{H}] \approx -1.50$ in the new UVES scale. We also identify the cluster’s blue straggler population. Comparing the radial distribution of these stars with the red giant branch population, we find that the blue stragglers are more centrally concentrated, as found in previous studies of blue stragglers in globular clusters. Taking advantage of the large field of view covered by our study, we analyzed the surface density profile of the cluster, and find extratidal main sequence stars out to $r \approx 14\arcmin$, or about twice the tidal radius. We speculate that the presence of these stars may be due to tidal disruption in the course of NGC 6981’s orbit, in which case tidal tails associated with the cluster may exist. We also take a fresh look at the variable stars in the cluster, recovering all previously known variables, including three SX Phoenicis stars. We also add three previously unknown RR Lyrae (one c-type and two ab-type) to the total census. Finally, comparing our CMD with unpublished data for M3 (NGC 5272), a cluster with a similar metallicity and horizontal branch morphology, we found that both objects are essentially coeval.

Key words: globular clusters: general – globular clusters: individual (NGC 6981, NGC 5272)

Online-only material: color figures

1. INTRODUCTION

Galactic globular clusters (GGCs) represent a key ingredient in the understanding of the evolution of the Galaxy, from both a chemical and stellar populations perspective. In particular, GGCs represent the oldest systems in the Milky Way and their relative ages accordingly play an important role in constraining the Galaxy’s formation timescale (e.g., Salaris & Weiss 2002; Marín-Franch et al. 2009; Dotter et al. 2010). A major advantage encountered in the study of globular clusters (GCs) is the frequent presence of large RR Lyrae populations, which are of great interest due to several properties of this class of objects, including their relative narrow range in magnitude (which makes them excellent standard candles to determine distances) and the presence of correlations between their pulsation properties and the properties of the GCs to which they belong (see, e.g., Zorotovic et al. 2010 and Cohen et al. 2011, for some recent examples).

Another remarkable characteristic of the RR Lyrae stars in GCs is the Oosterhoff dichotomy (Oosterhoff 1939, 1944), which consists of the sharp division of GC Lyrae systems into two groups, according to the average period of their ab-type (RRab; i.e., fundamental-mode) RR Lyrae population: Oosterhoff type I (OoI), with $P_{ab} \approx 0.55$ d, and Oosterhoff type II (OoII), with $P_{ab} \approx 0.65$ d. This dichotomous behavior applies exclusive to Galactic globulars, since nearby extragalactic systems somehow preferentially occupy a period range that is intermediate between groups OoI and OoII (Catelan 2009; M. Catelan et al. 2013, in preparation). In this sense, the Oosterhoff dichotomy provides important information that must be taken into account when studying the early formation history of the Milky Way and its dwarf satellite galaxy system. In this context, obtaining a complete census of the variability in GGCs is especially important, because such a census may help identify outliers in the Oosterhoff dichotomy context and hence potentially point to GCs of extragalactic origin.

Perhaps surprisingly, after more than a century of GGC variability studies, there is still a large number of GCs that lack time-series analyses, particularly using modern techniques. In this sense, the advent of CCD detectors, combined with sophisticated crowded-field photometry and image subtraction techniques (e.g., Stetson 1987, 1994; Alard & Lupton 1998; Alard & Lupton 1998; Alard & Lupton 1998; Bramich 2008) has proven to be of key importance for unveiling the presence of large numbers of previously unknown variable stars in GCs, particularly in their crowded cores.

According to the 2010 December version of the Harris (1996) catalog, the position of NGC 6981 is $\alpha = 20^h 53^m 27^s$9, $\delta = -12'32'13''$ (J2000) or $\ell = 35'16$, $b = -32'68$. This object has a low interstellar extinction of $E(B-V) = 0.05$. Very recently, Bramich et al. (2011) published the results of time-series imaging of this cluster, performed with difference imaging, and updated the cluster’s variable star census. In the framework of our long-term project to complete the census of variable stars in GGCs (Catelan et al. 2006), and with the advantage of a longer time baseline based on archival and new images, we have revisited the variability content of NGC 6981.
Importantly, with the large number of images used and a large fraction of the 1139 images in each of the photometric bands.

**Notes.** 1. Observer “CMR” 2. Observer L. Fulton 3. Observer A. R. Walker 4. Observer A. R. Walker 5. Observer A. R. Walker 6. Observer A. R. Walker 7. Observer H. E. Bond 8. Observer “DMD” 9. Observer unknown 10. Program ID 63.L-0342(B); ESO internal PI-COI ID 403; observer unknown 11. Program ID 63.L-0342(B); ESO internal PI-COI ID 403; observer unknown 12. Program ID 63.L-0342(B); ESO internal PI-COI ID 403; observer unknown 13. Program ID 69.D-0582(A); ESO internal PI-COI ID 361; observer unknown 14. PI unknown; observers C. Aguileria, J. Espinoza, A. Pasten 15. Program ID 59.A-9002(A); ESO internal PI-COI ID 50002; observer unknown 16. Proposal ID 2008A-289; observer A. R. Walker 17. Proposal ID 2008B-155; observer A. R. Walker.

The different cameras employed projected to different areas on the sky, and of course the telescope pointings differed among the various exposures. The WFI, WFC, Mosaic2, and EMMI imagers, in particular, consist of mosaics of non-overlapping CCD detectors. Therefore, although we have 1139 images, clearly no individual star appears in all those images. In fact, no star appeared in more than 169 B-band images, 200 V-band images, or 190 I-band images. Considering the entire area surveyed, the **median** number of observations for one of our stars is 13 in the B-band, 34 in the V-band, and 35 in the I-band. In the immediate vicinity of the cluster (within a radius of order 7 arcmin), however, most stars appeared in at least 100 images in each of the photometric bands.

There were insufficient U- and R-band images to define local standards in the NGC 6981 field, so we have not calibrated the U- or R-band data and make no use of them here. In addition,
during the 2008 August observing run on the CTIO Blanco 4 m telescope, three exposures (24 individual CCD images) were obtained in a DDO51 filter. This bandpass measures the strength of a molecular band of MgH and the “b” triplet lines of neutral magnesium, and can be used as a gravity/metallicity discriminator in very cool stars to distinguish likely member giants from foreground field dwarfs. While we do not employ the DDO51 data in our current investigation, we may revisit these data in a future study. Still, even though we do not make use of the $U$-band, $R$-band, and DDO51 data in our photometric analysis, these images were included in the ALLFRAME reductions for the additional information they give with respect to the completeness of the star list and the precision of the astrometry.

3. EXTRATIDAL STARS IN NGC 6981

The extended FOV available in our study motivates a new derivation of the tidal radius of NGC 6981. Several recent papers in which the surface brightness distribution of GGCs was studied have revealed evidence of the presence of extratidal stars (e.g., Walker et al. 2011, hereafter W11; Correnti et al. 2011; Carballo-Bello et al. 2012; Salinas et al. 2012). This result is not entirely surprising, for two main reasons. First, the number of wide-field CCD observations of GGCs has increased dramatically since the classical studies dealing with the structural parameters of these objects were published (e.g., Grillmair et al. 1995). Second, clusters are expected to undergo tidal disruption in the course of their lives, due to their interactions with the Galaxy as they orbit in the halo (e.g., Fall & Zhang 2001; Baumgardt & Makino 2003); and direct evidence of these interactions is being increasingly found in many GGCs (e.g., Odenkirchen et al. 2001, 2003; Grillmair & Johnson 2006; Jordi & Grebel 2010; Balbinot et al. 2011). Indeed, there is growing evidence that many GGCs may indeed have been much more massive in the past, some possibly being the remains of disrupted dwarf galaxies acting as building blocks in the hierarchical scenarios for galaxy formation (e.g., Boker 2008; Valcarce & Catelan 2011; Majewski et al. 2012, and references therein).

To study the structural parameters of NGC 6981 and to find the level of contamination by field stars, we followed the method described in W11, which is based on a similar dataset with a large FOV that extends more than 30′ from the cluster center. First, we identify an acceptance box in the $B − I$, $V$ plane, as shown in Figure 1. We used the $B − I$, $V$ plane, as suggested by W11, because of its stronger sensitivity to temperature, allowing a more robust determination of the ridgeline (more details on the ridgeline construction are given in Section 4.4). Also, the usage of all three filters available helps avoid spurious detections.

The selected box is assumed to contain most true cluster members, and so the number of bona-fide members falling outside this box is assumed to be small. The contamination from field stars inside the box is small but not negligible. We did not include in the acceptance box the blue straggler star (BSS) population, since it will have a very small effect on the estimation of overall number counts in the cluster and certainly will not affect the outer radii due to its mostly central concentration. More details on the BSS population are given in Section 4.4.

Once the acceptance box has been defined, the field is divided into concentric annuli, each with a radius of 50″, in order to study the radial density profile inside and outside the acceptance box. Since the cluster is not centered in the FOV, the limiting radius considered to be complete is the greatest circle within the FOV ($r \approx 14′.1$, which corresponds to the edge closer to the center of the cluster).

In Figure 2 (top panel) the logarithmic surface density of all stars outside the acceptance box is plotted, as a function of the inverse of the radial distance. Based on the assumption that the presence of true cluster members is negligible in the outermost annuli, it follows that the mean density value of the last points provides a reasonable estimate of the surface density of field stars outside the acceptance box. This assumption leads to an estimated field contribution of 5.8 stars arcmin$^{-2}$. We then calculated the fraction of stars inside and outside the box. In this case, the fraction of counts in each case is not affected by the incompleteness of the sample at radii beyond $r \approx 14′.1$, so we extended the annuli to the complete FOV. This fraction is shown in Figure 2 (middle panel). The asymptotic value (at larger distances) of the logarithm of this fraction approaches $−0.69 \pm 0.05$. Combining this number with the surface density of field stars outside the box, we obtain that the surface density of field stars is 7 stars arcmin$^{-2}$, comprised of 5.8 stars arcmin$^{-2}$ outside the box and 1.2 stars arcmin$^{-2}$ inside the box. The density profile of the cluster is shown in the bottom panel of Figure 2. The crosses correspond to the total density profile of the cluster and the filled circles are the surface density profile with the contamination of field stars subtracted. The error bars correspond to the Poissonian error in the number counts. In fact,
Figure 2. Top: logarithmic surface density as a function of the inverse of radial distance, for stars outside the acceptance box. The mean value corresponds to the surface density of field stars outside the box: \( \sim 0.8 \) stars arcmin\(^{-2} \). Middle: ratio between the number of stars inside the box and those outside the box, extending the annuli over the entire FOV. Bottom: surface density profile of NGC 6981, before (crosses) and after (filled circles) subtraction of field stars. The error bars are Poissonian.

(A color version of this figure is available in the online journal.)

The profile does not seem to break at \( r = 14.'1 \), nor show any indication of flattening at large distances.

An analysis of the CMD at different radial distances is shown in Figure 3. Here, no selection criteria were used for the stars. The selected annuli correspond to different values of the tidal radius of NGC 6981 found in the literature: \( r_t \approx 7.'4 \) is taken from the 2010 December version of the Harris (1996) catalog; this value was calculated based on the listed value of the central concentration \( c = \log(r_t/r_c) = 1.21 \), with \( r_c = 0.'46 \). The value \( r_t \approx 9.'2 \) is taken from Trager et al. 1995 and 14.'1 is the limit of our study. Figure 3 shows that there is still a trace of (mostly main sequence, MS) stars belonging to the cluster.
at radial distances further than \( r_t \approx 7.4 \) and even further than \( r_t \approx 9.2 \).

The existence of an extratidal component in NGC 6981, and in several other GGCs, was previously claimed by Grillmair et al. (1995). These authors concluded that these stars are probably unbound due to ongoing stripping episodes; furthermore, they speculated that GCs may not have observable limiting radii. These findings were also observed in \( N \)-body simulations (e.g., Combes et al. 1999; Capuzzo Dolcetta et al. 2005; Küpper et al. 2010, 2012). In our study, the derived density profile does not show flattening at larger distances. To put stronger constraints on the origin of the extratidal component of NGC 6981, it is important to cover more extended fields around the cluster.

4. COLOR–MAGNITUDE DIAGRAM

In Figure 1, we present the results from our photometry in the \( V, B-I \) plane for all stars (\( \approx 33,000 \)) detected in the three filters, throughout the field, with no selection criteria applied. The presence of field stars and background galaxies is clear, especially in the zone occupied by red giant branch (RGB) stars and the redder and fainter part of the CMD. To produce a tighter CMD, we applied standard selection criteria used before in similar studies based on ALLFRAME photometry (see Stetson et al. 2003). The initial cut was to consider stars with \( \sigma(B-I) \leq 0.1 \). Stars with values of \( \sigma(B-I) \) larger than 0.1 mag are mostly very faint stars (\( V \geq 23 \)). We then used the ALLFRAME index sharp, which gives an estimate of the residuals from the point-spread function (PSF) fit. We selected stars with \(-1 \leq \text{sharp} \leq 1\), which removed the contamination due mostly to background galaxies and very poorly measured stars. In order to obtain an accurate ridgeline and to study the more evolved populations, we applied one more cut based on the radial distance of the stars from the cluster center (e.g., Stetson et al. 2005). Figure 4 shows the distribution in magnitude of stars as a function of radial distance. The upper plot shows stars with \( \sigma(B-I) \leq 0.1 \), whereas the lower panel shows those with \( 0.1 \leq \sigma(B-I) \leq 0.3 \). For the sake of clarity, we have marked in the upper plot the limits at \( V = 20, r = 100', \) and \( r = 316' \). This figure suggests that
CMD reveals an overall morphology in good agreement with that obtained after applying the described selection criteria. The purpose of obtaining a cleaner CMD is to remove contamination and improve the detection limit for stars with good photometry within the magnitude range $18 \leq V \leq 20$ is at a radius of $\approx 30''$. Moreover, we can consider that the detection limit for stars with $V \geq 20$ is constant from radii greater than 100'' until $\approx 316''$, where there appears to be a break before field contamination increases at fainter magnitudes. We summarize all these considerations by applying the following radial selection criteria:

$$
V \leq 18 \quad \text{and} \quad r \leq 316'', \\
18 \leq V \leq 20 \quad \text{and} \quad 30'' \leq r \leq 316'', \\
20 \leq V \leq 30 \quad \text{and} \quad 100'' \leq r \leq 316''.
$$

We remark that, as stated in the previous section, the limit of 316'' does not correspond to the cluster’s tidal limit; it is used only for the purpose of obtaining a cleaner CMD.

In Figure 4, we plot the cleaner CMD in all available filters, obtained after applying the described selection criteria. The CMD reveals an overall morphology in good agreement with previous studies (Dickens 1972; Piotto et al. 2002; Bramich et al. 2011), but this study reveals a more extended MS, reaching down to $V \approx 24$, and with errors less than $\approx 0.1$ mag at this faint level. Also, we note the presence of a well-defined RGB with moderate steepness, a horizontal branch (HB) with both red and blue populations, a relatively populated asymptotic giant branch sequence, and the presence of a BSS population.

In Figure 5, we plot the cleaner CMD in all available filters, obtained after applying the described selection criteria. The CMD reveals an overall morphology in good agreement with previous studies (Dickens 1972; Piotto et al. 2002; Bramich et al. 2011), but this study reveals a more extended MS, reaching down to $V \approx 24$, and with errors less than $\approx 0.1$ mag at this faint level. Also, we note the presence of a well-defined RGB with moderate steepness, a horizontal branch (HB) with both red and blue populations, a relatively populated asymptotic giant branch sequence, and the presence of a BSS population.

As in many previous studies, including for instance Stetson et al. (2005) and Zorotovic et al. (2009), the mean ridgelines for the $B − V$, $V − I$, and $B − I$ versus $V$ planes were determined by eye in large-scale plots. Then, the normal points were overplotted in the CMD to perform some minor adjustments to obtain a smooth ridgeline. The fiducial points are presented in Tables 2–4, and the resulting ridgeline, in the $B − I$ versus $V$ plane, is overplotted on the data in Figure 3. We note that the apparent asymmetry of the MS around the fiducial line is probably due to a binary sequence. Sollima et al. (2007) estimated a binary fraction for NGC 6981 of $\xi \approx 10\%$, based on Hubble Space Telescope/Advanced Camera for Surveys photometry.

The zero-age horizontal branch (ZAHB) level was determined in the same way as in Ferraro et al. (1999, hereafter F99; see their Figure 3), by fitting the Victoria-Regina ZAHB models (VandenBerg et al. 2006) at $\log T_{\text{eff}} = 3.85$, assuming $[\text{Fe/H}] = -1.41$ and $[\alpha/\text{Fe}] = +0.3$ (recall that the cluster

| $V$         | $B - V$ |
|-------------|---------|
| 0.79        | 23.10   |
| 0.61        | 22.01   |
| 0.52        | 21.36   |
| 0.48        | 20.74   |
| 0.47        | 20.30   |
| 0.48        | 20.01   |
| 0.51        | 19.85   |
| 0.56        | 19.74   |
| 0.59        | 19.70   |
| 0.64        | 19.60   |
| 0.65        | 19.54   |
| 0.68        | 19.30   |
| 0.72        | 18.70   |
| 0.75        | 18.00   |
| 0.78        | 17.40   |
| 0.84        | 16.80   |
| 0.91        | 16.20   |
| 1.03        | 15.50   |
| 1.20        | 14.70   |
| 1.30        | 14.30   |
| 1.42        | 14.00   |

| $V$         | $B - I$  |
|-------------|----------|
| 1.90        | 23.55    |
| 1.78        | 23.20    |
| 1.64        | 22.80    |
| 1.55        | 22.53    |
| 1.45        | 22.22    |
| 1.36        | 21.92    |
| 1.30        | 21.70    |
| 1.23        | 21.41    |
| 1.17        | 21.05    |
| 1.13        | 20.80    |
| 1.12        | 20.60    |
| 1.11        | 20.40    |
| 1.12        | 20.21    |
| 1.14        | 20.03    |
| 1.17        | 19.92    |
| 1.23        | 19.80    |
| 1.30        | 19.72    |
| 1.37        | 19.66    |
| 1.45        | 19.59    |
| 1.50        | 19.44    |
| 1.56        | 19.04    |
| 1.62        | 18.57    |
| 1.68        | 17.90    |
| 1.75        | 17.37    |
| 1.82        | 16.88    |
| 1.91        | 16.46    |
| 2.00        | 16.09    |
| 2.11        | 15.68    |
| 2.22        | 15.35    |
| 2.36        | 14.98    |
| 2.47        | 14.73    |
| 2.60        | 14.50    |
| 2.75        | 14.25    |
| 2.87        | 14.13    |
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Figure 5. BVI photometry for NGC 6981, in the \( V, B-V \) plane (left), \( V, B-I \) plane (middle), and \( V, V-I \) plane (right). Selection criteria according to Figure 4 were applied (see the text for details).

Table 4
Mean Fiducial Points for NGC 6981: \( V, V-I \) Plane

| \( V \)     | \( V-I \) |
|------------|-----------|
| 0.64       | 20.66     |
| 0.65       | 20.04     |
| 0.68       | 19.86     |
| 0.72       | 19.75     |
| 0.76       | 19.70     |
| 0.79       | 19.62     |
| 0.83       | 19.52     |
| 0.85       | 19.38     |
| 0.87       | 19.05     |
| 0.89       | 18.63     |
| 0.91       | 18.12     |
| 0.94       | 17.62     |
| 0.99       | 16.90     |
| 1.04       | 16.34     |
| 1.11       | 15.73     |
| 1.18       | 15.27     |
| 1.26       | 14.82     |
| 1.36       | 14.43     |
| 1.42       | 14.21     |
| 1.51       | 14.00     |

has \([\text{Fe}/\text{H}]=-1.42\), according to the 2010 December version of the Harris 1996 catalog, and that halo stars typically have a similar such level of \( \alpha \)-element enhancement; see, e.g., Pritzl et al. 2005). We matched the ZAHB in the dereddened CMD (using a value of \( E(B-V)=0.05 \); see Section 4.1 for details) by allowing vertical shifts. The result is shown in Figure 6. In this way, we found \( V_{\text{ZAHB}}=16.89\pm0.02 \) mag, in good agreement with the value listed in F99 for NGC 6981. The turn-off (TO) point was determined by fitting a parabola to the data.

Figure 6. NGC 6981 CMD zoomed in around the evolved sequences of the CMD. The solid black line corresponds to a Victoria-Regina model ZAHB (VandenBerg et al. 2006) with \([\text{Fe}/\text{H}]=-1.41\) and \([\alpha/\text{Fe}]=+0.3\). The dashed line is the inferred ZAHB level, at \( V=16.89\pm0.02 \). The dashed horizontal lines denote the levels 2.0 and 2.5 mag above the HB in \( V \). The solid vertical red line is defined by the color of the RGB at the HB level, \( (B-V)_h \). The solid vertical blue lines intersecting the ridgeline at the upper RGB indicate the \( \Delta V \) measurements at \( (B-V)_h = 1, 1.2, \) and 1.4, respectively. See Section 4.1 for more details.

(A color version of this figure is available in the online journal.)
points in a small area of the MS around the TO. We obtain $V_{\text{TO}} = 20.31 \pm 0.1$ mag at a color $(B - I)_{\text{TO}} = 0.47$ mag.

**4.1. Reddening and Metallicity**

The 2010 December version of the Harris (1996) catalog lists the reddening for NGC 6981 as $E(B - V) = 0.05$, based on previous photometric studies. For comparison, the Schlegel et al. (1998) dust maps give $E(B - V) = 0.06$. We adopted the Harris value for the remainder of our analysis.

F99 reviewed observational indicators that are derived from the evolved sequences in the CMD and can be used to estimate photometric metallicities (see their Table 4). We used the dereddened $B - V$, $V$ plane to measure the parameters $(B - V)_{0, g}$ (intrinsic color of the RGB at the HB level), $S_{2.0}$, $S_{2.5}$ (slope of the line connecting the point of intersection between the RGB and the HB level and the point 2.0 and 2.5 magnitudes brighter than the HB, respectively), $\Delta V_{1.1}$, and $\Delta V_{1.2}$ (height of the RGB bump) as a function of global metallicity. The data are taken from Amigo et al. (2001; empty diamonds). The filled circle indicates the value derived for NGC 6981 in our study.

**4.2. Metallicity and Strength of the RGB Tip**

The 2010 December version of the Harris (1996) catalog lists the reddening for NGC 6981 as $E(B - V) = 0.781$, $\Delta V_{1.1} = 1.96$, $\Delta V_{1.2} = 2.39$, $S_{2.0} = 6.07$, $S_{2.5} = 5.59$, as suggested in F99. The results are

| Parameter | $[\text{Fe}/\text{H}]_{\text{CG97}}$ | $[\text{M}/\text{H}]_{\text{CG97}}$ | $[\text{Fe}/\text{H}]_{\text{UVES}}$ | $[\text{M}/\text{H}]_{\text{UVES}}$ |
|-----------|-----------------------------------|-----------------------------------|-------------------------------|-----------------------------|
| $(B - V)_{\text{TO}}$ | 0.781 | -1.42 | -1.21 | -1.61 | -1.42 |
| $\Delta V_{1.1}$ | 1.96 | -1.29 | -1.10 | -1.47 | -1.28 |
| $\Delta V_{1.2}$ | 2.39 | -1.38 | -1.18 | -1.57 | -1.38 |
| $S_{2.0}$ | 6.07 | -1.03 | -1.23 | -1.18 | -0.98 |
| $S_{2.5}$ | 5.59 | -1.48 | -1.23 | -1.69 | -1.49 |
| Mean | -1.32 | -1.19 | -1.50 | -1.31 |

brighter than the HB at color $(B - V)_{\text{TO}} = 1.1, 1.2$, as shown in Figure 6. The very red star close to the RGB tip level, at a color $B - V \approx 1.7$, corresponds to the variable star V42 (Figure 13). This star is found to vary, but the type of variability is not identified and it may not be a member of the cluster (see Section 6 for details). For this reason, we avoid extrapolating the ridgeline to reach this star, and the parameter $\Delta V_{1.4}$ was not used in this work.

The values of the parameters obtained in our study as well as the resulting values for $[\text{Fe}/\text{H}]$ (in the Carretta & Gratton 1997, CG97, metallicity scale) and $[\text{M}/\text{H}]$ are summarized in Table 5. Taking the mean, the final adopted values are $[\text{M}/\text{H}] = -1.19 \pm 0.05$ and $[\text{Fe}/\text{H}] = -1.32 \pm 0.17$.

It should be noted that recently, Carretta et al. (2009) presented a recalibration of the CG97 metallicity scale, based on a homogeneous analysis of a large sample of spectra taken with UVES. The relation between both scales is

$$[\text{Fe}/\text{H}]_{\text{UVES}} = 1.137(\pm0.060)[\text{Fe}/\text{H}]_{\text{CG97}} - 0.003,$$

as provided in their study. The CG97 values were transformed to this scale and are also summarized in Table 5. The final metallicity value adopted in this paper, in the UVES scale, is $[\text{Fe}/\text{H}] = -1.50 \pm 0.19$. Similarly, we transformed the values of $[\text{M}/\text{H}]$ in Table 5 to the UVES metallicity scale using the theoretical equation found by Salaris et al. (1993), used in F99, this time using the new UVES $[\text{Fe}/\text{H}]$ values

$$[\text{M}/\text{H}]_{\text{UVES}} = [\text{Fe}/\text{H}]_{\text{UVES}} + \log(0.638 f_\alpha + 0.362),$$

where $f_\alpha$ is the enhancement factor of the $\alpha$ elements; in this case we use $f_\alpha = 100.28$, as suggested in F99. The results are shown in column 5 of Table 5.
Since the slopes $S_{2.0}$ and $S_{2.5}$ do not depend on the adopted reddening, we use those values and the obtained value of $[\text{Fe/H}]$ to find, for the reddened color of the RGB at the HB level, a value $(B-V)_\odot = 0.82$. This fact leads to a reddening value of $E(B-V) = 0.039$, in good agreement with our adopted value.

Other methods to determine reddening are based in the minimum light colors of ab-type RR Lyrae stars (a description of the RR Lyrae population and other variables appears in Section 6). Indeed, over the phase range $0.5 < \phi < 0.8$, the intrinsic colors of RRab stars are fairly uniform (e.g., Preston & Spinrad 1959; Preston 1964). Therefore, we also estimated the reddening using Sturch’s method (Sturch 1966; Walker 1990), a relation between color at minimum light, period, and (more weakly) metallicity, as described by Walker (1998), where the reddening is calculated with the following relation:

$$E(B-V) = (B-V)_\text{min} - 0.24 P - 0.056[\text{Fe/H}] - 0.036,$$

where $(B-V)_\text{min}$ is the color of the RRab star at minimum light, $P$ is the fundamental period of the variable in days, and $[\text{Fe/H}]$ is the metallicity in the Zinn & West (1984; ZW84) scale. We use our result listed in Table 5 in the UVES scale, and transformed to the ZW84 scale using the second-order polynomial relation provided by Carretta et al. (2009), giving a value of $[\text{Fe/H}] = -1.57$. By only considering stars with $\sigma(B-V)_\text{min} < 0.06$ mag, we obtain a reddening value of $E(B-V) = 0.08$ mag, which is slightly higher than our adopted value. As shown by Guldenschuh et al. (2005), the $(V-I)_\text{0,min}$ colors of ab-type RR Lyrae stars are also remarkably uniform, with $(V-I)_\text{0,min} = 0.58 \pm 0.02$ mag, irrespective of period, amplitude, and metallicity (Kunder et al. 2013). We calculated the $V-I$ color at minimum light from our data and on this basis we found a mean value of $E(V-I) = 0.07$ mag, or $E(B-V) = 0.06$ mag, assuming $E(V-I) = 1.27 E(B-V)$—as obtained from Equation (1) in Dean et al. (1978), for $(B-V)_0 \approx 0.3$ mag (as appropriate for RR Lyrae stars) and $E(B-V) \approx 0.05$ mag. This result is in excellent agreement with our adopted value. It is worth noting that higher reddening values for NGC 6981 have on occasion been favored in the literature, including, for instance, $E(B-V) = 0.07$ mag (de Santis & Cassisi 1999) and $E(B-V) = 0.11$ mag (Rodgers & Harding 1990).

### 4.2. RGB Bump

An important feature of the RGB is the presence of a well-defined peak in its luminosity function (LF). This peak is known as the RGB bump and was first predicted by Thomas (1967) and Iben (1968) as a consequence of the encounter of the H-burning shell and the chemical composition discontinuity left behind after the convective envelope reaches maximum depth during the first dredge up. This process produces an increase in the H abundance, which causes a sudden drop in the mean molecular weight $\mu$. Since the efficiency of the H-burning shell is proportional to a high power of $\mu$, the luminosity decreases (Cassisi et al. 2011). Evolution of stars in this stage slows down while the stars adjust to the new conditions, resulting in an overdensity in the LF. The RGB bump, first detected by King et al. (1985), is known to be located at higher luminosities for more metal-poor GCs (e.g., Fusi Pecci et al. 1990; Recio-Blanco & de Laverny 2007). The position of the RGB bump is
important for studying the evolutionary properties of RGB stars (e.g., Catelan 2007 and references therein).

To determine the position of the bump, we followed a method similar to the one described in Zoccali et al. (1999). We select the RGB stars in the CMD, restricting ourselves to those stars within \( r \leq 316'' \), to avoid field contamination (Figure 7, top). Although it is possible that some field stars are present in the selected RGB sample, these should be sufficiently few that our final result is not affected.

The LF constructed for the selected stars is shown in Figure 7 (middle panel). We constructed an average-shifted histogram (Scott 1985) by combining eight different histograms, each calculated in an interval in magnitude of \( \Delta V = 4 \) and with a bin width of 0.25 mag but with different origin values \( x_0 = 14, 14.2, 14.4, 14.6, \) and 14.8 mag. This method of smoothing a dataset allows us to determine a significant peak in the data that does not depend on the choice of bin width and origin. Figure 7 (bottom) displays the cumulative distribution. The change in the slope corresponds to the position of the RGB bump. Based on these plots, the location of the bump was measured at \( V_{\text{bump}} = 16.6 \) mag.

F99 studied the relation between \( \Delta V_{\text{HB}} \) (the difference in magnitude between the RGB bump and the ZAHB level) and the metallicity of the cluster, confirming a strong correlation between these quantities. The relation is shown in Figure 8, for [Fe/H] and global metallicity [M/H] in the CG97 scale. The data were taken from Table 5 in F99. The solid circle represents the value for NGC 6981 found in this study, with \( \Delta V_{\text{HB}} = -0.29 \) mag. Our result is clearly consistent with the correlation found in F99.

Another useful parameter involving the RGB bump is \( \rho_{\text{bump}} \), defined in Bono et al. (2001). This quantity is the ratio between the number of RGB stars in the bump region (i.e., at \( V_{\text{bump}} \pm 0.4 \)) and the number of RGB stars in the interval \( V_{\text{bump}} + 0.5 < V < V_{\text{bump}} + 1.5 \). This parameter is an indicator of the occurrence of deep mixing before the H shell encounters the chemical discontinuity left over by the first dredge up, which would have an effect on the time spent in the bump region. In Figure 9, we plot the data taken from Bono et al. for \( \rho_{\text{bump}} \) as a function of global metallicity. For NGC 6981, we obtained a value of \( \rho_{\text{bump}} = 0.61 \pm 0.10 \) (solid circle in Figure 9). Bono et al. found a large value of \( \rho_{\text{bump}} \) for NGC 6981, mostly due to a small number of bump stars (\( N_{\text{bump}} = 40; \) see their Table 1). We found instead \( N_{\text{bump}} = 58 \), which leads to a slightly smaller \( \rho_{\text{bump}} \) value, more consistent—but still not completely so—with other clusters with similar metallicities. As found by Bono et al., this plot shows that the bulk of metal-poor clusters do not experience deep mixing before stars reach the bump.

### 4.3. HB Morphology

The HB of NGC 6981 (Figure 6) does not show any prominent features, such as an extended HB or gaps in the blue part, so it can be well described by the HB index \( \mathcal{L} = (B - R)/(B + V + R) \) (Lee et al. 1994), were \( B, R, \) and \( V \) correspond to the numbers of blue, red, and variable (RR Lyrae-type) stars on the HB, respectively. To obtain the counts in each case, we selected stars within a radius of 100′′to avoid field star contamination, particularly in the red HB; however, the inclusion of a couple of stars from the RGB, scattered by photometric errors, might be possible. This method yields a value of \( \mathcal{L} = +0.02 \), slightly less than the value of \( \mathcal{L} = +0.14 \) listed by Mackey & van den Bergh (2005). Another significant parameter is \( \rho_{\text{HB}} = (B2 - R)/(B + V + R) \) (Buonanno 1993), where \( B2 \) corresponds to the number of stars in the HB with dereddened colors in the interval \( -0.02 < (B - V)_0 < 0.18 \). This parameter was introduced in order to overcome the saturation of the \( L \) parameter for extreme blue HB morphologies. With the same constraints as before, we found \( \rho_{\text{HB}} = -0.27 \) for NGC 6981.
4.4. BSS Distribution

BSSs are a subpopulation present mostly in the cores of GCs. They appear as a brighter and hotter extension of the MS in the CMD, beyond the cluster’s TO point, suggesting the presence of stars more massive than normal MS stars. There are currently two main scenarios to explain the origin of BSSs: mass transfer between primordial binaries and direct collisions of stars in dense environments (see Ferraro & Lanzoni 2009 for a recent review). These two scenarios are non-exclusive and can even coexist (Ferraro et al. 2009).

Because of their high masses compared with normal MS stars, BSSs are expected to be highly concentrated in the cluster centers. In fact, the radial distribution of BSSs is typically bimodal, which is explained in terms of mass segregation and the nature of their progenitors (Mapelli et al. 2006; recent examples are found in Carraro & Sleznev 2011 and Salinas et al. 2012), but in some cases, the radial distribution of BSSs might be flat (see Beccari et al. 2011 and Contreras Ramos et al. 2012 for examples), indicating the presence of younger, not-yet-segregated populations.

The BSS population of NGC 6981 is clearly identified in Figure 10, framed by the selection box applied. We also selected a subsample from the RGB in order to compare both populations. The boxes were chosen in order to avoid the regions of the CMD with spurious blends. For the determination of the cumulative radial distribution of BSSs, we chose as a limit the tidal radius at \( r_t = 7.4 \), from Harris (1996, 2010 edition; see Section 3). The extratidal component found in Section 3 contains mostly MS stars and it is too small to study the BSSs. Within the tidal radius, we found 39 BSSs and 330 RGB stars. The cumulative radial distribution for both populations is displayed in Figure 11. This finding provides direct evidence for a more centrally concentrated distribution of
BSSs, supporting mass segregation. A Kolmogorov–Smirnov test reveals that the probability of the two populations being drawn from the same parent distribution is less than 0.1%.

5. RELATIVE AGE DETERMINATION: COMPARISON WITH M3

To obtain a relative age for NGC 6981, we compared this study with unpublished photometry for M3. This cluster has a similar metallicity (according to the 2010 December version of the Harris 1996 catalog, $[\text{Fe/H}]_{\text{M3}} = -1.50$) and its CMD morphology resembles that of NGC 6981. The ridgeline and the TO point of M3 were determined using the same method described in Section 4 for NGC 6981. The $V$ magnitude of the HB was obtained using the Victoria-Regina ZAHB models, in the same way as with NGC 6981, assuming $[\text{Fe/H}] = -1.41$ and $[\alpha/\text{Fe}] = +0.3$. For M3, we determined the TO magnitude level and the HB level to be $V_{\text{TO}} = 19.08 \pm 0.1$ mag and $V_{\text{HB}} = 15.66 \pm 0.02$ mag, respectively. In the case of NGC 6981, we recall from Section 4 the values $V_{\text{TO}} = 20.31 \pm 0.1$ mag and $V_{\text{ZAHB}} = 16.89 \pm 0.02$ mag.

The difference in magnitude between the HB and TO levels are related to age according to the following relation:

$$\Delta \log t_\odot = (0.44 + 0.04[\text{Fe/H}]) \Delta$$

\[ \text{(5)} \]
(Buonanno et al. 1993), where $\Delta = (\Delta V_{\text{HB}}^{\text{GC1}}) - (\Delta V_{\text{HB}}^{\text{GC2}})$ and $t_9$ is the age in Gyr. For M3, we obtained $\Delta V_{\text{HB}}^{\text{M3}} = 3.44$, whereas for NGC 6981 we found $\Delta V_{\text{HB}}^{\text{NGC6981}} = 3.42$. These numbers lead to an age difference of $\Delta \log t_9 \sim 0.008$, which translates to about 0.2 Gyr, around 12 Gyr (using $\Delta t_9 = t_9 \ln(10) \Delta \log t_9$), in the sense that M3 is formally older—but essentially implying that M3 and NGC 6981 are coeval, to within the errors.

Another way to approach this issue is to compare directly the M3 and NGC 6981 CMDs. This comparison is done in Figure 12, where the ridgeline obtained for NGC 6981 is overplotted on the M3 photometry. Both the data and the ridgeline have been dereddened, using the $E(B-V)$ values from the 2010 December version of the Harris (1996) catalog. The ridgeline of NGC 6981 has been shifted 1.3 mag brighter, to account for the difference in distance modulus with respect to M3. The RGBs of the two clusters match reasonably well, confirming that they have similar metallicities. Also, the match in luminosity of their subgiant branches confirms that the ages of the two clusters are basically indistinguishable.

6. VARIABLE STARS REVISITED

Bramich et al. (2011, hereafter B11) published a revised catalog of variable stars in NGC 6981, based on $V$-, $R$-, and $I$-band photometry. This investigation was the first variability study for this cluster in $\sim 40$ yr, using CCD imaging and differential image analysis techniques. Fourteen new variable stars were discovered, leading to a total census of 43 variable stars, including 40 RR Lyrae stars and 3 SX Phoenicis (SX Phe) stars (see their Table 2).

With the advantage of having a longer time baseline, we have revisited the variability in NGC 6981. We discovered three new RR Lyrae stars, including two fundamental-mode (RRab) and one first-overtone (RRc) pulsators. Following the B11 notation, we catalog these stars as V57, V59, and V60 (V58 is discussed in the text below). The remainder of the variables found in B11 were recovered (including the SX Phe stars) and, in some cases, we have improved the phased light curve and the period determination. Concerning the Blazhko (1907) effect, which is characterized by a long-term modulation of the light curve amplitude and shape, we confirmed the presence of the effect, claimed by B11, in V11, V14, V15, V23, V28, V31, V32, V36, and V49; the effect was also present in V35, V39, V51, and V53. Although V10 was also claimed to show the Blazhko effect, we found no evidence in the phased light curve.

The coordinates, periods, and variability types are provided in Table 6 and Figure 13 displays the positions of the variables in the CMD. In some cases, B11 could not study stars with previous claims of variability, due to technical limitations.
provide light curves for these stars in Figures 14 through 18, with comments on a few individual stars given in the next section.

After this paper had been submitted, Skottfelt et al. (2013) announced the discovery of a new variable star in NGC 6981, namely V57. The classification and period of the variable matches our findings, but there is a discrepancy in the star’s coordinates (they provide $\alpha = 20^\mathrm{h}53^\mathrm{m}27^\mathrm{s}.12$, $\delta = -12^\circ32'13.9''$). Moreover, they report another (unclassified) variable, with a period of 0.285 d, at a position near V57 in our catalog ($\alpha = 20^\mathrm{h}53^\mathrm{m}27^\mathrm{s}.38$, $\delta = -12^\circ32'13.3''$). The reason for this discrepancy is unknown; however, we note that the coordinates provided in our work match reasonably well those provided by B11. To avoid confusion regarding the variable census, we kept their catalog identification for this variable.

6.1. Comments on Individual Stars

V27 and V35: These variables were detected by Dickens & Flinn (1972) and were originally classified as ab-type RR Lyrae; however, in the study of B11, they appeared out of the FOV, so even though B11 include them in their final catalog, no new periods could be determined. We confirmed the RRab type for V27 and V35, with a period of 0.673871 d and 0.543749 d, respectively (Figure 14), consistent with the periods listed by Dickens & Flinn. We also note that V35 displays the Blazhko (1907) effect.

V38 and V42: According to B11, Sawyer (1953) and Dickens & Flinn (1972) discovered that these stars were variable, but they were unable to provide a light curve because V38 was proximate to a saturated star and V42 was itself saturated. In our analysis, V38 shows no sign of variability. In the case of V42, the light curve was phased with a period of 1.01109 d, as shown in Figure 15. In the CMD, the star is located at the red extension of the bright RGB, with a position consistent with that expected for the RGB tip, if the star is a bona-fide cluster member. Such short periods for bright RGB stars are quite unusual. The proximity of the period to 1 d renders the derived period suspicious. On the other hand, barring saturation effects, the variability amplitude, of order 0.5 mag in the $B$-band, 0.3 mag in the $V$-band, and 0.2 mag in the $I$-band, seems quite significant.

V39: This star shows no variability in B11, mostly due to outlier photometric measurements. In this study, we found evidence of variability and its light curve was phased with a period of 0.426785 d. The morphology of the light curve was...
suggests a RRab classification. The Blazhko (1907) effect might also be present. However, we note that the star is fainter than the bulk of the cluster’s RR Lyrae population, with $V = 17.95$ mag (see Figure 13). Thus, V39 may be a field variable, and we have accordingly not included this star in our calculations of reddening and HB morphology parameters.

V44, V45, V52, and V53: B11 do not provide any periods for these stars, since each of them suffered from poor phase coverage due to the closeness of a saturated star affecting the light curve. We present here the improved light curves in Figures 14 and 16, and their derived periods are given in Table 6. V51: B11 listed a period of 0.357335 d, although they noted that the period was not reliable due to poor phase coverage and blending. In fact, the light curve they provided does not show the maximum. Here, we provide a more reliable period of 0.548599 d, and our well-sampled light curve is shown in Figure 16.

6.2. SX Phoenicis Stars

The number of SX Phe stars in GCs has increased markedly in recent years. These variables are of particular interest because they are located in the BSS zone in the CMD. Recently, Cohen & Sarajedini (2012) compiled an updated SX Phe stars catalog in GCs, establishing a period-luminosity relation for the sample. In the future, we hope that the pulsation properties of SX Phe stars will shed light on BSS formation and evolution.

In our study, we have recovered all three SX Phe stars found in B11. Using Period04 (Lenz & Breger 2005) to analyze the Fourier diagrams, the periods found correspond to the frequency of the largest amplitude oscillation and the pulsation mode could not be identified in two cases, V55 and V56, with V-band amplitudes of 0.22 and 0.08 mag, respectively. Since there are no non-radial pulsators with $A_V > 0.15$ (Cohen & Sarajedini 2012), V55 is likely a radial pulsator. However, the argument does not go in the other direction: double radial-mode pulsators may have $A_V < 0.15$ and even some fundamental-mode SX Phe stars may have small amplitudes. In the case of V54, we detected two significant frequencies with a ratio of $f_1/f_2 \approx 0.78$, which are likely to correspond to the fundamental mode ($f_2$) and the first radial overtone ($f_1$; Olesch et al. 2005). This result is consistent with what B11 found for these stars. The periods of V54 and V56 are slightly different from those given in B11, while for V55 we obtained a good agreement (see Figure 17 for the phased light curves). It should be noted that in the case of V56 we could not be identified in two cases, V55 and V56, with what B11 found for these stars. The periods of V54 and V56 are slightly different from those given in B11.

In conclusion, we recover all three SX Phe stars found in B11. Based on the measured RGB color and slope, we infer that the cluster has a metallicity [Fe/H] $\approx -1.50$ in the new UVES scale. We firmly detect the cluster’s blue straggler population, which is found to be more centrally concentrated than the RGB component. We also find evidence of extratidal cluster stars being present out to $r \approx 14\prime.1$, or about twice NGC 6981’s tidal radius, and speculate that tidal tails associated with the cluster may exist. Finally, we revisit the variable star content of the cluster, recovering all previous known variables, including three SX Phe stars. We also discover three previously unknown RR Lyrae (one c-type and two ab-type).

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