Variability in NGC 3201 Giant Stars and Its Impact on Their Spectroscopic [Fe/H] Determination

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Received 2020 July 6; revised 2020 November 26; accepted 2020 November 29; published 2021 January 20

Abstract

We present the analysis of 34 light curves in V and J of 17 giant stars in the globular cluster NGC 3201 to check if such stars are variable and if their variability has some kind of impact on the iron abundance as obtained from spectroscopic measurements. First, we computed the generalized Lomb–Scargle and phase dispersion minimization periodograms of the sample to check if the stars were variables. In this way, seven stars of the sample were found to be nonvariable, two stars are considered as possible variables, and eight stars were found to be variable, with periods ranging from 0.0881 ± 0.0001 to 0.5418 ± 0.0027 days. According to the literature, the variables have distinct values of [Fe I/H]: the three most metal-rich stars are in the red giant branch (RGB) stage, one has [Fe I/H] = −1.37 dex, while the other two have [Fe I/H] = −1.31 dex. The two most metal-poor variables have [Fe I/H] = −1.61 dex and [Fe I/H] = −1.62 dex, and are AGB stars; the remaining variables have [Fe I/H] = −1.44, −1.48, and −1.50 dex, the first two being RGB stars while the last is an AGB star. On the other hand, stars that appear to be nonvariable have −1.56 ≤ [Fe I/H] ≤ −1.40. We conclude that variability somehow affects the spectroscopic determination of the iron content of giant stars in NGC 3201, increasing the iron spread of the cluster. If variability is not taken into account, this spread could be incorrectly interpreted as due to an intrinsic iron spread affecting the stars of the cluster.

Unified Astronomy Thesaurus concepts: Globular star clusters (656); Stellar abundances (1577)

1. Introduction

In several respects, globular clusters (GCs) have remained one of the most relevant astronomical objects of study over more than 100 years. They were at first thought to be examples of simple stellar populations, which was later proven to be incorrect owing to detailed chemical analyses showing that almost all GCs display inhomogeneities in their light-element contents (e.g., Gratton et al. 2004; Carretta et al. 2009a, 2009b). The most prominent feature is the Na–O anticorrelation, with Ruprecht 106 (Villanova et al. 2013) being the sole exception to date. But there are also GCs that display a metallicity distribution or iron spread; ω Centauri (e.g., Origlia et al. 2003; Pancino et al. 2011; Marino et al. 2011) and Terzan 5 (e.g., Origlia et al. 2011, 2013), both displaying a multimodal distribution spanning a range of ∼1 dex, and M54 (e.g., Bellazzini et al. 2008; Carretta et al. 2010; Mucciarelli et al. 2017), although its metallicity distribution is not as large as that in ω Cen and Terzan 5.

In recent years, several studies have been made with the objective to find other GCs displaying an intrinsic iron spread; however, they present smaller inhomogeneities than ω Cen, Terzan 5, and M54. Examples of such clusters are M22 (Marino et al. 2009), NGC 3201 (Simmerer et al. 2013), M2 (Yong et al. 2014), NGC 5286 (Marino et al. 2015), and M19 (Johnson et al. 2015). Some of these works have been reevaluated by other studies to either confirm the intrinsic spread in the metallicities or conclude that those findings were not correct at all.

NGC 3201 (C1015—461) is a nearby (∼4.9 kpc), low galactic latitude (b = +8°64) GC located at α = 10h 17m 36s 52, δ = −46° 24′ 44″ 9 (2000) (Harris 1996, 2010 edition). Its [Fe/H] content is controversial, because different analyses have yielded notably different results. For example, the study of González & Wallerstein (1998), which used CTIO high-resolution spectra, and that of Simmerer et al. (2013), which employs high-resolution spectra from UVES-FLAMES@VLT and MIKE@Magellan, claim that NGC 3201 has a spread in [Fe/H] of ∼0.4 dex. However, Muñoz et al. (2013) do not find such spread, deriving [Fe/H] = −1.53 ± 0.01 dex, and also point out that five out of the six most metal-poor stars—with [Fe/H] ≤ −1.59 dex—from Simmerer et al. (2013) might be asymptotic giant branch (AGB) stars instead of red giant branch (RGB) stars.

Mucciarelli et al. (2015) reanalyzed the spectra of 21 stars from the sample of Simmerer et al. (2013) in light of the results of Lapenna et al. (2014), who proposed nonlocal thermodynamic equilibrium (NLTE) effects as an explanation for the lower Fe abundances of AGB stars compared to those observed in RGB stars. By adopting photometric gravities that use the Stefan–Boltzmann equation and measuring Fe I and Fe II lines individually, they discovered that the spread found in Simmerer et al. (2013) was due to the presence of AGB stars in the sample and concluded that NGC 3201 does not have an intrinsic iron spread. It should be noted, however, that for GCs with metallicity similar to NGC 3201, NLTE correction models from Bergemann et al. (2012) and Lind et al. (2012) predict that the Fe I lines should be affected in a similar way regardless of whether the star is an RGB or an AGB star, and thus there should be another mechanism that could explain the behavior of the iron content of the cluster.

In this context, it is important to note that red giant stars are unstable against radial pulsations; in fact, as stars evolve, expanding and cooling into the RG or AGB stages, they become pulsationally unstable, meaning that—virtually—every star found in the upper-right portion of the H-R diagram is a
variable. Moreover, pulsating red giants (PRGs) are complex objects, mainly due to their variability being the result of a mix of pulsation and convection (this not yet being a well-understood process in astrophysics), and because of the presence of extended atmospheric envelopes (Catelan & Smith 2015). Olin Eggen published a series of papers during the 1970s (e.g., Eggen 1973, 1977) in which he developed a general classification for PRGs: large-, medium-, and small-amplitude red variables (LARV, MARV, and SARV, respectively), along with the σ Librae variables, stars with amplitudes less than 0.2 mag in V. Pulsating red giants are characterized by having a long period and a short amplitude.

As a first clue to a possible relation between variability and iron abundance in red giants, recently Muñoz et al. (2018) analyzed the chemical abundance of seven stars of NGC 6528 and found that one of the RGB stars of the sample was (1) more metal poor, with [Fe/H] = −0.55, than the other six stars—having a mean value of [Fe/H] = −0.14 ± 0.03, and that (2) it was a variable star with a period of 0.26 days and an infrared amplitude of 0.05 mag, using data from the VVV survey (Minniti et al. 2010; Saito et al. 2012). These findings prompted us to ask ourselves the following question: can the variability of a star be related to its observed difference in iron abundance, compared with that of the rest of the stars that are not variable? To seek an answer, we decided to revisit one of the GCs whose iron content is debated, NGC 3201. As a further motivation, it is worth pointing out that Layden & Sarajedini (2003) reported low-amplitude light variations in several RGB stars in this cluster.

In this paper, we present a study of 34 light curves (LCs) of 17 giant stars—17 in V and 17 in I—of the GC NGC 3201. First, we try to determine the possible variability of each star within the limitations of our data. Then, for the possible variables, we then searched the literature for their [Fe/H] content. The aim is to check whether or not these giant stars are variables and if such variability is somehow related to their iron abundance as obtained from spectroscopic data using standard data analysis. The layout of this paper is as follows. In Section 2, we present information regarding the data employed in the work. Section 3 provides details of the methodology followed to analyze the sample. Section 4 contains the main results obtained from our analysis. In Section 5, we present a discussion of our findings. Finally, in Section 6 we summarize the results and give the conclusions obtained from this work.

2. The Data

For this work, we analyzed 34 LCs (17 in the V filter and 17 in the I filter) of 17 giant stars from NGC 3201 provided by J. Ahumada, previously published in Arellano Ferro et al. (2014). These stars were also analyzed by Simmerer et al. (2013) and Mucciarelli et al. (2015), who determined their [Fe/H] abundance. Each LC for the V filter contains 142 epochs, and for the I filter, 4 LCs (Stars N° 2, 5, 6 and 15) are based on 144 epochs, while the other 13 contain 145 epochs. Figures 1 and 2 show the LCs of all stars in the V and I filter, respectively, and Table 1 displays a portion of the complete content of each LC.

The data for all 17 giant stars were obtained on 2013 March 20–23 at the Complejo Astronómico El Leoncito (CASLEO), San Juan, Argentina, using the 2.15 m telescope, carrying out Johnson–Kron–Cousins V and I observations. The detector used was a Roper Scientific back-illuminated CCD of 2048 × 2048 pixels with a scale of 0.15 pix−1 and a field of view of approximately 5.1 × 5.1 arcmin2. The data reduction and transformation to the Vl standard magnitude system are described in Sections 2.2 and 2.3 of Arellano Ferro et al. (2014).

The finding chart of the stars that were analyzed in this work is in Figure 3. It is worth noting that Stars N° 8 and 10 are close to each other, while Stars N° 1, 6, 7, and 9 have close (although
faint) neighbor stars. In spite of this, contamination from these neighbors on the spectra used to obtain \([\text{Fe}/\text{H}]\) seems unlikely. This is because slit spectrographs like MIKE@Magellan can easily avoid neighbor contamination by just rotating the camera, and in any case, during the reduction process the spectrum of a contaminating star can be successfully subtracted from that of the target. Fiber spectrographs like UVES-FLAMES@VLT have fibers that are only 1" in diameter, and neighbors stars visible in Figure 3 are not close enough to affect the incoming light.

In order to identify our stars of interest, we matched them with the ones from Mucciarelli et al. (2015) using both position (R.A. and decl.) and mean magnitudes \(\langle M_V \rangle\) and \(\langle M_I \rangle\) for the V and I filters, respectively. We also matched our stars with those from the variable star catalog by Clement et al. (2001) using the Tool for OPerations on Catalogues And Tables (TOPCAT) to see if any of our stars were already cataloged as variable, where we did not find any match at all. This is not surprising because there are very few studies in the literature about variability in

\[\text{Table 1} \]

Sample Time Series for the V and I Filters of Each Star

| Star | Filter | HJD (d) | \(M_{\text{std}}\) (mag) | \(\sigma_{M_{\text{std}}}\) (mag) | \(\sigma_{\text{int}}\) (mag) |
|------|--------|---------|--------------------------|--------------------------|--------------------------|
| No 1 | V      | 2456371.522859 | 13.93920 | 0.0078 | 0.00074 |
| No 1 | V      | 2456371.525984 | 13.94512 | 0.0079 | 0.00063 |
| No 1 | I      | 2456371.517222 | 12.62022 | 0.0092 | 0.00085 |
| No 1 | I      | 2456371.519717 | 12.61734 | 0.0093 | 0.00080 |
| No 2 | V      | 2456371.522859 | 12.89581 | 0.0090 | 0.00043 |
| No 2 | V      | 2456371.525984 | 12.89554 | 0.0090 | 0.00035 |
| No 2 | I      | 2456371.517222 | 11.36980 | 0.0095 | 0.00043 |
| No 2 | I      | 2456371.519717 | 11.37122 | 0.0099 | 0.00041 |

Note. Columns 1 and 2 display the number of stars in Figure 1 and 2 and the filter, respectively. Column 3 shows the epoch of mid-exposure in heliocentric Julian days (HJD), column 4 shows the standard magnitude, column 5 gives the errors associated with the standard magnitudes, and column 6 gives the internal errors associated with the DanDIA reduction program.

Figure 2. Light curves of the 17 stars in the I filter analyzed in this work. Same as in Figure 1: the x-axis corresponds to the heliocentric Julian days (HJD) and the y-axis shows the standard magnitude I. The black ellipses mark the three epochs that were affected by bad photometry and regarded as outliers.

Figure 3. Finding chart of the area of NGC 3201 where the 17 giant stars analyzed in this work are indicated. These stars were studied previously by Simmerer et al. (2013) and Mucciarelli et al. (2015). West is up, north is to the left, and the area shown is \(5.4 \times 5.4\).
GC giant branch stars. Table 2 shows the main information of each star, and Figure 4 shows the color–magnitude Diagram (CMD) of the cluster with the position of the stars studied in this work marked with different symbols depending on if they were classified as variable, nonvariable, or a possible variable, as explained in Section 4.  

3. Analysis of the Light Curves and the Search for Variability

To check the possible variability of each star, we applied both the generalized Lomb–Scargle (GLS; Zechmeister & Kürster 2009) and the phase dispersion minimization (PDM; Stellingwerf 1978) methods. We must first note that, for all stars observed in the I filter, there are three epochs taken in the fourth night, which are indicated with an ellipse in Figure 2. These epochs show evidence of having been affected by bad photometry and were therefore rejected for our analysis on the grounds that they are outliers.

Both analyses were performed in Python using the PyAstronomy package collection (Czesla et al. 2019). The code requires as input the observation time, the data (in this case magnitudes), and (optionally) the errors associated with them (columns 3, 4, and 5 of Table 1, respectively), along with a starting period ($P_{\text{beg}}$) and an end period ($P_{\text{end}}$).

The frequency step utilized for the analysis is given by the equation

$$f_{\text{step}} = 1.0 / (\text{Time Length}) / OFac,$$

with Time Length being HJD$_{\text{end}}$ – HJD$_{\text{beg}}$, and OFac the Oversampling Factor, which has a value of 10. The GLS analysis also carries out a false-alarm probability (FAP), which is used to check which periods are significant enough. The FAP is given by

$$\text{FAP}(P) = 1 - \left(1 - \text{Prob}(P > P_0)\right)^M,$$

where $M$ is the number of independent power values, computed internally by the program and $\text{Prob}(P)$ is the probability that a periodogram power $P$ has to exceed a given value $P_0$. This function depends on the periodogram and on the normalization.

After performing the GLS analysis, the program carried out the PDM analysis for the star using the same parameters as before, viz., starting period, end period, and frequency Step. Figure 5 shows an example of the periodograms obtained for Star N° 8 with the GLS (top panels) and PDM (bottom panels) methods, with the left and right panels being the results for the $V$ and $I$ filters, respectively.

In order to check if a giant in our sample can be considered as a candidate variable star or not, we adopted the following criteria:

1. The inequality $A + \sigma_A > \text{rms}_{\text{mag}}$ must be satisfied for both filters, with $A$, $\sigma_A$, and $\text{rms}_{\text{mag}}$ being the amplitude, its error, and the rms of the magnitude data, respectively. These parameters are given by the GLS analysis.
2. The possible periods must display their peaks above the FAP threshold of 0.1% in the GLS periodogram for both filters.
3. The periods $P_{\text{GLS}}$ and $P_{\text{PDM}}$ must be similar for both filters.
4. The possible period must be present in both filters, and $P_V \approx P_I$.
5. The visual inspection of the LCs must show that they maintain a constant mean magnitude along the four nights of observation.

Adopting these criteria, the stars discarded as nonvariables are N°s 6, 7, 10, 12, 14, and 15.

### 3.1. Significance Test

The purpose of this section is to present how we determined which giant could be a candidate variable or not, as well as to determine the degree of variability of each star through a significance test.
For this purpose, we first calculate the magnitude difference $\Delta M$ for each star, defined as

$$\Delta M = M - \langle M \rangle,$$

with $\langle M \rangle$ being the mean magnitude of the star. As in the preliminary analysis, the three bad data points of the fourth night in the $I$ filter (indicated with ellipses) affected the measurement of $\langle M \rangle$ and, as a consequence, $\Delta M$, and therefore were discarded.

After obtaining $\Delta M$ for all 17 giant stars, we first calculated $s = \sum (\Delta M - \langle M \rangle)^2 / N - 1$ and its error $\text{err}_s = s / \sqrt{2N}$ for the six objects that were discarded as nonvariable, using the data of all those stars combined together for each filter, which we named $\sigma_{\text{Non Var.}}$ and $\text{err}_{\text{Non Var.}}$. This represents the variance of a typical nonvariable star. Then, we proceeded to calculate $\sigma_{\text{Star}}$ and $\text{err}_{\text{Star}}$ for the remaining 11 candidate variables to determine their significance $S$ (for each filter), given by

$$S = \frac{\sigma_{\text{Star}} - \sigma_{\text{Non Var.}}}{\sqrt{\text{err}_{\text{Star}}^2 + \text{err}_{\text{Non Var.}}^2}}.$$

To find out whether or not the star could be a variable, we adopted the following criteria based on the value of $S$ (Equation (3)):

1. If $S < 2$ for both filters, the star is not considered a variable.
2. If $S > 3$ for both filters, the star is considered a variable.
3. If $S > 3$ in one of the filters, the star is considered a possible variable.

4. If $2 < S < 3$ in one or both filters, the star is considered a dubious variable and requires further analysis for confirmation.

For stars in cases (ii), (iii), and (iv), we reperformed the period analysis described in the previous section by carefully adjusting the different parameters from the PyAstronomy routines, while stars in case (i) were not reanalyzed. Table 3 shows the values of $S$ derived for all candidate variables along with the classification according to the above criteria. One star—N° 11—was rejected as a variable due to its low values of $S_V$ and $S_I$, which are below 2. Six stars—N°s 1, 2, 3, 5, 8, and 9—were regarded as variables, as $S_V > 3$ and $S_I > 3$ for all of them, and their LCs from Figure 1 and Figure 2 show a clear change in their magnitudes each night. Four stars were considered as possible variables (N°s 4, 13, 16, and 17) and were reanalyzed to see if they could be variables or candidates for future investigations. No star was classified as a dubious variable.

### 4. Analysis of the Sample of Giants

In this section, we repeated the period analysis of the 10 stars that were considered variable or a possible variable according to the results listed in Table 3 (Section 3.1). The final classification of our targets is reported in Table 5. For the analysis of the variable stars, we have considered their characteristics and position in the CMD (Figure 4) and compared their LCs with existing variable stars.

#### 4.1. Variable Stars

In this section, we will describe in detail each variable star found in this work. We applied again to the stars N° 1, 2, 3, 4,
5, 8, 9, 13, 16, and 17 the period analysis described in
Section 3, and we could confirm that stars 4 and 17 are also
variable. Table 4 details the parameters for all of the con-
firmed variable stars, and Figure 6 shows their phased LCs for both
filters. Each night is represented by a different color. We will
also compare their LCs with known variables taken as
reference from the Optical Gravitational Lensing Experiment
(OGLE) Atlas of Variable Star Light Curves6 (Udalski et al.1997; Szymanski2005; Udalski et al.2008)
in order to attempt
a classification. We consider also Yepez et al. (2018), where
the authors study variability in the GC NGC 6934 and identify
a kind of variable in the giant branch of the cluster named
semiregular (SR), the LC of which resembled the LCs of some
of our targets. We underline the fact that in some cases, the

| Star | $S_V$ | $S_I$ | Classification |
|------|------|------|----------------|
| N° 1 | 14.719 | 14.874 | Variable |
| N° 2 | 11.695 | 8.311 | Variable |
| N° 3 | 3.524 | 4.885 | Variable |
| N° 4 | 0.490 | 3.900 | Possible |
| N° 5 | 12.648 | 8.596 | Variable |
| N° 8 | 11.013 | 7.833 | Variable |
| N° 9 | 4.800 | 3.162 | Variable |
| N° 11 | 0.000 | 0.000 | Nonvariable |
| N° 13 | 2.454 | 0.990 | Possible |
| N° 16 | 0.880 | 5.769 | Possible |
| N° 17 | 0.000 | 7.570 | Possible |

Figure 5. Resulting plots from the GLS (top panels) and PDM (bottom panels) analysis performed with the PyAstronomy package collection for the $V$ and $I$ filters (left and right panels, respectively). Both results are from the initial period analysis of Star N°8. From the GLS analysis, one can see the different FAP level thresholds indicated with the different colored dashed lines, with blue being 10%, yellow 5%, green 1%, and red 0.1% probability. In the PDM analysis, the black dashed line indicates the minimum value of $\Theta$. Note that the GLS analysis for the $I$ filter is the only one that marks a different period ($P = 0.0811$ days) compared to the ones marked by GLS in the $V$ filter and PDM for both filters.

6 http://ogle.astrouw.edu.pl/atlas/index.html
Table 4
Periodicity Parameters for All Stars that Presented a Variable Behavior

| Star | $P_V$ (days) | $\sigma_{P_V}$ (days) | $A(V)$ (mag) | $\sigma_{A(V)}$ (mag) | $P_I$ (days) | $\sigma_{P_I}$ (days) | $A(I)$ (mag) | $\sigma_{A(I)}$ (mag) | $M_V$ (mag) | $M_I$ (mag) |
|------|--------------|-----------------------|--------------|-----------------------|--------------|-----------------------|--------------|-----------------------|--------------|--------------|
| No 1 | 0.5418       | 0.0027                | 0.0591       | 0.0025                | 0.5417       | 0.0023                | 0.0556       | 0.0021                | 13.9393      | 12.6293      |
| No 2 | 0.5329       | 0.0026                | 0.0266       | 0.0012                | 0.5417       | 0.0043                | 0.0116       | 0.0008                | 12.8925      | 11.3689      |
| No 3 | 0.3527       | 0.0037                | 0.0064       | 0.0007                | 0.3429       | 0.0034                | 0.0050       | 0.0006                | 13.5405      | 12.1394      |
| No 4 | 0.1628       | 0.0008                | 0.0047       | 0.0005                | 0.1628       | 0.0007                | 0.0053       | 0.0006                | 13.8897      | 12.6326      |
| No 5 | 0.4827       | 0.0024                | 0.0331       | 0.0013                | 0.4772       | 0.0032                | 0.0114       | 0.0009                | 12.8158      | 11.3473      |
| No 8 | 0.0881       | 0.0001                | 0.0195       | 0.0012                | 0.0881       | 0.0002                | 0.0072       | 0.0004                | 13.8944      | 12.6193      |
| No 9 | 0.5281       | 0.0054                | 0.0081       | 0.0006                | 0.5164       | 0.0067                | 0.0058       | 0.0005                | 13.7802      | 12.4272      |
| No 17| 0.3535       | 0.0035                | 0.0045       | 0.0005                | 0.3535       | 0.0021                | 0.0093       | 0.0007                | 13.8238      | 12.4290      |

Figure 6. Phased light curves of our eight variable stars found in this work which were plotted by phasing the light curve of each star with their corresponding period $P_V$ shown in Table 4. The top panel of each phased light curve corresponds to the phased curve in the V filter and the bottom panel the phased light curve in the I filter. The different colors indicate the data taken during each night of observation. For the top panel, Night 1 is green, Night 2 cyan, Night 3 yellow, and Night 4 blue. For the bottom panel, Night 1 is red, Night 2 magenta, Night 3 orange, and Night 4 purple.
reference best-match variables have different parameters (mass, temperature, and gravity) compared with our targets and also are located at a different evolutionary phase. In any case, this comparison can give us important hints about the physical mechanism behind the variability of our targets. We notice first that confirmed variables have two kind of LCs. The first, represented by stars 1, 8, and 17, shows a sudden rise in magnitude followed by a slow drop. The second, represented by stars 2, 3, 4, 5, and 9, shows the opposite behavior, a slow rise followed by a fast drop.

*Star No 1.* This star has a period $P = 0.5418 \pm 0.0027$ days, with an amplitude $A > 0.055$ mag in both filters. It shows a clear variable behavior in $V$ and $I$ (Figure 1 and 2) and a clear phased LC (Figure 6(a)). At first, for the $V$ filter, the GLS analysis showed us a period of $P \sim 1.1135$ days if we considered $P_{\text{end}} = \text{Time Length}$, but the PDM analysis marked $P \sim 0.55996$ days, while in the $I$ filter both the GLS and PDM analysis displayed a period between 0.5413 and 0.55457 days. The longest period obtained from the GLS analysis of the $V$ filter is almost twice the period obtained from the PDM analysis of the same filter and from the GLS and PDM analysis of the $I$ filter, and it could have been considered as the actual period. However, the phased LC of this star displayed with such a period was not realistic, which led us to discard it. Finally, after restricting the $P_{\text{end}}$ value to $P < 1$ day, we obtained the period listed in Table 4. It is worth noting that this star is positioned in the lower part of the RGB (see Figure 4), and by comparing its phased LC with known variables, it resembles an RR Lyrae ab star and the period is similar to some of the known RRab. However, its low amplitude does not agree with these types of variables.

*Star No 2.* This star displays an evident magnitude difference, as shown in both LCs (Figure 1 and Figure 2). For this case, the period analysis indicates that this star has a period $P = 0.5329 \pm 0.0026$ days, but the phased LC shown in Figure 6(b) does not display a complete curve. This is due to the diurnal interruption of the observations. Figure 4 shows that this star is positioned at the top of the RGB, and Figure 7 shows that its phased LC resembles that of an SR variable like V96 described by Yepez et al. (2018) in the RGB of the GC NGC 6934 and is located in a similar position of the CMD near the tip. However, because SR variables display large periods, in this particular case, V96 has a period of 9.54 days, we cannot attempt to classify this star as an SR due to the discrepancy between these parameters. We do however note that the period shown for this star is similar to those displayed in RR Lyrae stars.

*Star No 3.* The $V$-filter LC of this star shows quite a small difference in magnitude, while in $I$ it is more evident, particularly during the third night. From the results obtained after a more precise analysis, we found a period $P = 0.3527 \pm 0.0037$ days. This star is positioned in the CMD in the middle part of the RGB, and Figure 6(c) shows the phased LC where a small but clear variability is visible with its period resembling that of pulsating variables (e.g., RR Lyrae stars). Figure 7, as in the case of Star No 2, shows that its phased LC is similar to the one from V96 described by Yepez et al. (2018) in the RGB of the GC NGC 6934. But both its location in the CMD and both the period and amplitude do not agree with these kind of variables.

*Star No 4.* This particular star was also considered a possible variable candidate due to the significance values from Table 3, with $S_V < 2$, but $S_I > 3$. We therefore reperformed our period analysis with more caution and detail. This star shows similar values of $P$ from the GLS method for both filters, while for the PDM method the situation was unclear. However, after restricting the $P$ interval and taking caution that the periodogram does not display the estimated period as the only possible one, both methods yielded similar values of $P$, with the final result being $P = 0.1628 \pm 0.0008$ days (Table 4). Figure 4 shows that this star is located in the lower part of the giant branch. The phased LC of this star is in Figure 6(d), and as with the previous star, Figure 7 shows that its phased LC could resemble that of an SR variable like V96. However, like Star No 3, the period shown for this star does not agree with the period of typical SR stars. We also note that the phased LC of this star could also resemble that of an RR Lyrae–type RRc displaying a similar period to those kinds of variables, but we went for the SR variable due to better resemblance of its phased LC.

*Star No 5.* This star shows a quite clear variable behavior as far as the $V$ filter is concerned, while for the $I$ filter the variability is not clear (see Figure 1 and 2). The variability analysis shows that this star has a period $P = 0.4827 \pm 0.0024$ days; its phased LC is reported in Figure 6(e). We can also see that this star, from its position in the CMD, displays a similar case to Star No 2, located at the top of the giant branch and displaying a period similar to those found in RR Lyrae variables. Figure 7 shows that its phased LC is similar to that of V96 from Yepez et al. (2018), but again its period and amplitude do not agree with these types of variables.

*Star No 8.* This star displays a period $P = 0.0881 \pm 0.0001$ days and was the one that presented the most prominent variability along with Star No 1 although with a smaller amplitude; it was also the star on which we performed all of the parameter testing from the methodology presented in Section 3, where we tested how the PyAstronomy routines worked and adjusted the final parameters in order to have precise results. Similar to the case of Star No 1, this star’s position in the CMD is in the lower part of the RGB, with its phased LC resembling more like a δ Scuti star, but with an amplitude lower than these types of stars (see Figure 7). Figure 6(f) shows the phased LC of this star for the $V$ and $I$ filters.

*Star No 9.* This star displayed a variable behavior in its $V$-filter LC. The $I$-filter LC also displays a variability, although not as evident as in the $V$ filter. After performing our analysis, the most probable period for the $V$ filter was $P = 0.5281 \pm 0.0054$ days. The PDM method for the $I$ filter also suggested another period of $P \sim 0.3417$ days, which, however, is much less probable than the first one. From Figure 4, we can see that this star is positioned at the lower part of the AGB with its period similar to those found in typical RR Lyrae stars, and Figure 7 shows that its LC resembles that of an SR variable like V96 from Yepez et al. (2018); however, as in other stars that were compared with the SR V96, its period and amplitude do not agree at all with this kind of variable. The left panel of Figure 6(g) displays the phased LC for this star.

*Star No 17.* Its LC for the $V$ filter does not display an evident variable behavior, but its LC in $I$ does show evident variability in magnitude, which can be seen in the plot from the fifth row, first column of Figure 2. Due to this feature and also to its significance $S_I$ value from Table 3, which is higher than 3, we reperformed our period analysis, obtaining a period $P = 0.3535 \pm 0.0035$ days and the amplitudes $A(V)$ and $A(I)$ shown in Table 4. Also, based
on the shape of its phased LC, like Stars No 1 and 8, its variable behavior is similar to that of a pulsating variable, like an RR Lyrae or a Cepheid. In this case, we chose Cepheid as the best match (see Figure 7), but again its low amplitude value makes it difficult to provide such classification. The phased LC of this star is shown in the right panel of Figure 6(h).

4.2. Possible Candidates

In this section, we present the two stars that, despite not showing a clear variable behavior compared to the eight stars presented in the previous section, are considered as possible variables according to the results of our period analysis and are good targets for future studies using a more complete multiepoch photometric approach.

Star No 13. This possible variable star is interesting because both LCs displayed a variable behavior during the third night (although quite small). The GLS method derived a period $P = 1.0614$ days but the PDM analysis showed a period $P = 0.6983$ days, even though the second-highest probability period for the GLS analysis was at $P = 0.5287$ days (top panels of Figure 8). We adjusted the PyAstronomy parameters...
to evaluate the other periods. It is worth noting that there are two more periods above the 0.1% threshold at $P \sim 0.41564$ days and $P \sim 0.33818$ days, but the amplitudes derived by the GLS analysis were equal to (if not lower than) the mean magnitude error, so they were rejected. Figure 9 shows the phased LCs of the three different periods. Future observations for this star could help determine if this star is a real variable and, if so, its variability period.

**Star No 16.** This particular star was challenging because its LC for the $V$ filter did not present any magnitude variation, but for the $I$ filter it displayed a peculiar behavior during the third night (fourth row and fourth column panel of Figure 2). We derived two different periods for the $V$ and $I$ filters ($P_V = 0.3981$ days and $P_I = 0.4174$ days, left and right panels of Figure 10, respectively), as in the case of Star No 13, future observations could help to determine if this star is a real variable and, if so, its variability period.

If the variability behavior of star 13 and 16 is confirmed, a classification could be possible for both stars in a similar manner to the case of our variable stars from Section 4.1.

### 4.3. Variability and Its Possible Impact on the Spectroscopic $[\text{Fe/H}]$ Determination

After finishing our period analysis of the variable stars, the next step was to check if their variable behavior has an impact on the $[\text{Fe/H}]$ determination as obtained from spectra. First of all, we used the abundance study of NGC 3201 by Mucciarelli et al. (2015), who measured the iron abundance by adopting photometric values of $\log g$. They used photometric gravities...
based on the results of Lapenna et al. (2014), who suggested that NLTE effects could affect the abundances in AGB stars that are obtained from Fe I lines, although the abundances from Fe II lines appear not to be modified. This effect can be detected by assuming photometric values of $g_{\log}$ and measuring the abundances from Fe I and Fe II independently. They also remarked that RGB stars do not display such effects.

We point out here that AGB and RGB stars in the sample have very similar atmospheric parameters. For this reason, if they are affected by NLTE, the final Fe I abundances should suffer the same change, independently of the evolutionary stage.

We grouped each star according to their classification given in Section 3 and Section 4—variable, nonvariable, and possible variable—and, with the [Fe I/H] values shown in Table 2, we plotted the significance $S_V$ (top panels) and $S_I$ (bottom panels) against their [Fe I/H] for each group in the left panel of Figure 11. In this figure, we can see that stars that have extreme [Fe I/H] values are variables, i.e., the most metal-poor stars like Star No 8 ([Fe I/H] = −1.61 ± 0.03) and No 4 ([Fe I/H] = −1.62 ± 0.03) and the most metal-rich like Stars No 1 and No 17 with [Fe I/H] = −1.31 ± 0.03, and Star No 2 with [Fe I/H] = −1.37 ± 0.02 are located at the extremes of the [Fe I/H] distribution. However, the three remaining variables, i.e., Stars No 3, 5, and 9, have a metallicity that agrees well with that of the nonvariable sample. This could indicate, as we will infer in the discussion from the study of For et al. (2011), that the [Fe I/H] metallicity as obtained from the spectra could depend on the phase at which the spectrum is taken. Furthermore, we note that stars that are not variable and those which are possible variables (Section 4.2) have [Fe I/H] values that are close to the mean value of the [Fe I/H] of the total sample.

We also checked the [Fe II/H] content of each variable star to see if it shows a similar behavior. The right panels of Figure 11 show the significance values of the variable stars, possible variables, and nonvariables plotted against [Fe II/H]. From this figure, we can see that variable stars tend to have on average higher [Fe II/H] values compared with nonvariable stars and that, as in the case of [Fe I/H], variable stars show a higher spread degree in comparison with the possibles and nonvariables.
parameters are obtained from photometry as in Mucciarelli et al. (2015). On the other hand, the effect on the iron spread is important. We see in fact that variable stars have a much higher iron spread regardless of the method used to obtain the parameters. The spread for variable stars is up to twice the values obtained for nonvariables. This effect must be taken into account in any study of intrinsic iron spread of stellar populations, especially in GCs, otherwise the wrong conclusion could be that the cluster hosts stars with different metallicities.

5. Discussion

At this point, it is interesting to check where the different groups of stars lie in the CMD of Figure 4. We see there that variables are distributed evenly among RGB and AGB stars, with three objects being AGBs and four being RGBs. On the other hand only two nonvariables appear to be AGBs against five RGBs. In any case, we cannot reach any firm conclusion about a possible relation between variability and the evolutionary phase due to the limited sample we have.

Regarding the possible mechanism responsible for the variability, we note that the LC of three of our targets 1, 8, and 17 closely resembles those of stars whose variability is caused by radial or nonradial pulsations (RR Lyrae, δ Scuti, and Cepheid, respectively). From that we deduce that pulsation is very likely the cause of the variability of our stars and that it is related to the spread in the spectroscopic [Fe/H] determination we observe.

At this point, it is also worth mentioning the possibility that the variability we observe is not intrinsic to the RGB or AGB stars we are studying, but it is due to an unresolved blending with other variables of the cluster. In order to check this hypothesis, we will analyze here the three stars #1, #8, and #17 because they show an LC very similar to that of pulsating variables (e.g., RR Lyrae). Because of this and because the only known variables bright enough to affect the V and I magnitude of giant stars in NGC 3201 are RR Lyrae (Arellano Ferro et al. 2014), we will consider only these objects as the
possible polluters of the LC. Figure 13 shows the position in the CMD of our three stars (squares) and of the known RR Lyrae (red circles). The aim is to know what the real position of the three targets would be if we remove the contamination from the RR Lyrae.

If we have two blended stars (stars A and B), the equation to calculate the magnitude of A using the total magnitude (A + B) and the magnitude of B (in our case a RR Lyrae) can be obtained from Pogson’s equation and is

$$m_A = m_B - 2.5 \log(10^{-(m_{\text{tot}}-m_B)/2.5}) - 1.$$ 

We applied this equation to the V and I magnitudes of the three stars using the V and I mean magnitudes of all the RR Lyrae. The result is the three strips of circles in Figure 13. As we can see, if the hypothesis of the blending is true, the three targets would fall well out of the RGB of the cluster. They could still be giants, but much more metal rich than the value obtained from spectroscopy ([Fe/H] < −1.4). They would also fall in a region completely empty of stars, and they will not be compatible with being members of the clusters, at odds with what was found in all the spectroscopic studies we mention in previous sections.

Another test we can do is to calculate the probability of finding a blend between a giant stars and an RR Lyrae. In order to do that, we first have to define the area around a target where, if an RR Lyrae falls, we have an unresolved blend. Because the FWHM of the observation was around 2″, it is safe to assume a circular area with a radius of the same size. Because the field of view (FOV) is 5.4′ × 5.4′ (see Figure 3) and in Figure 13 we identify 35 RR Lyrae, we find that that

Figure 11. Left panels: significance values $S_V$ and $S_I$ for each star plotted against their respective [Fe I/H] measurements from Mucciarelli et al. (2015). The green stars represent the variable stars, the red squares represent the nonvariables, and the blue dots represent the possible candidate variables. Right panels: significance values for each star plotted against their [Fe II/H] measurements from Mucciarelli et al. (2015) plotted with the same x-axis scale as the left panel and the different colors for each group of stars are the same as in the left panels.
Table 5
Final Classification, Iron Abundance Information, and Significance Values of the 17 Giant Stars

| Star | Classification | [Fe/H] (dex) | [Fe I/H] (dex) | [Fe II/H] (dex) | \(S_V\) | \(S_I\) |
|------|----------------|-------------|---------------|----------------|--------|--------|
| 1    | Variable       | −1.48       | −1.31 ± 0.03  | −1.29 ± 0.05   | 14.719 | 14.874 |
| 2    | Variable       | −1.42       | −1.37 ± 0.02  | −1.40 ± 0.05   | 11.695 | 8.311  |
| 3    | Variable       | −1.54       | −1.48 ± 0.02  | −1.43 ± 0.04   | 3.524  | 4.885  |
| 4    | Variable       | −1.79       | −1.62 ± 0.03  | −1.37 ± 0.04   | 0.490  | 3.900  |
| 5    | Variable       | −1.53       | −1.50 ± 0.02  | −1.40 ± 0.04   | 12.648 | 8.596  |
| 6    | Nonvariable    | −1.45       | −1.47 ± 0.02  | −1.45 ± 0.05   | 0.0    | 0.0    |
| 7    | Nonvariable    | −1.65       | −1.54 ± 0.02  | −1.39 ± 0.03   | 0.0    | 0.0    |
| 8    | Variable       | −1.71       | −1.61 ± 0.03  | −1.38 ± 0.04   | 11.013 | 7.833  |
| 9    | Variable       | −1.56       | −1.44 ± 0.02  | −1.44 ± 0.05   | 4.800  | 3.162  |
| 10   | Nonvariable    | −1.64       | −1.56 ± 0.02  | −1.42 ± 0.04   | 0.0    | 0.0    |
| 11   | Nonvariable    | −1.50       | −1.40 ± 0.02  | −1.45 ± 0.05   | 0.0    | 0.0    |
| 12   | Nonvariable    | −1.54       | −1.43 ± 0.03  | −1.43 ± 0.04   | 0.0    | 0.0    |
| 13   | Possible       | −1.51       | −1.45 ± 0.02  | −1.45 ± 0.04   | 2.454  | 0.990  |
| 14   | Nonvariable    | −1.52       | −1.50 ± 0.02  | −1.45 ± 0.04   | 0.0    | 0.0    |
| 15   | Nonvariable    | −1.46       | −1.44 ± 0.03  | −1.44 ± 0.06   | 0.0    | 0.0    |
| 16   | Possible       | −1.59       | −1.54 ± 0.02  | −1.38 ± 0.04   | 0.880  | 5.769  |
| 17   | Variable       | −1.45       | −1.31 ± 0.03  | −1.29 ± 0.05   | 0.0    | 7.570  |

Note. The [Fe/H] values are from Simmerer et al. (2013), while the [Fe I/H] and [Fe II/H] values are from Mucciarelli et al. (2015).

Figure 12. Top panel: plot displaying the significance values \(S_V\) of the 17 stars against their [Fe/H] abundance from Simmerer et al. (2013). Bottom panel: significance values \(S_I\) of the 17 giants plotted against their [Fe/H]. The colors for both panels are the same as in Figure 11. For the error bar, we assumed an error on [Fe/H] of 0.05 dex, which is the typical error for a purely spectroscopic measurement.

Figure 13. CMD of NGC 3201 showing how photometric blending between a giant star and a variable star could affect the position of stars 1, 8, and 17 from this work. Red stars are all known RR Lyrae from the cluster, while our stars are marked in different colors: Star No1 is blue, No 8 is magenta, and No 17 is yellow.

probability of a blend is

\[
P = \frac{\text{Area}_{\text{FOV}} \cdot N_{\text{RR Lyrae}}}{0.004}.
\]

If we calculate then the probability of having three stars affected by a blend, we end with a total probability of

\[
P_{\text{TOT}} = P^3 = 0.00000007.
\]

These numbers can vary if we change our inputs such as the FOV, the size of the circular area, or if we consider that RR
Lyrae are not uniformly distributed in the FOV but they follow a King density profile. In any case, the probability we calculated is low enough to ensure that, together with the CMD position test, none of the LCs of our targets is the result of a blend between a regular RGB or AGB and a variable star.

In order to further discuss the impact of variability on spectroscopic [Fe/H] determinations, it is worth commenting here the paper by For et al. (2011), where the abundances of 11 RR Lyrae ab-type variables were studied. They analyzed more than 2300 high-resolution spectra from the 2.5 m du Pont telescope distributed along the period curve of each variable. In Figure 14, we overplot the [Fe/H] abundances of each variable, where a single measurement of each variable was divided by the corresponding mean [Fe/H] abundance. Figure 14 indicates that a variable can show a variation in [Fe/H] up to ±0.2 dex, depending on the phase. This means that a variable can have an excursion of up to 0.4 dex in its [Fe/H] content. In addition, the mean [Fe/H] behavior is quite regular with the phase, at least between midphases 0 and 0.6. At midphase = 0 the deviation from the mean iron abundance is around zero. Then the deviation increases toward higher metallicities reaching its maximum at midphase = 0.2. It remains constant until midphase = 0.4 and then returns to zero at midphase = 0.6. After that, the behavior is quite chaotic, with some variables showing a positive deviation of 0.1 dex or more, while others show a negative deviation of −0.15 dex or more. On the other hand, the maximum deviation in this plot is between −0.3 and + 0.3 dex. Such finding is important because it is an independent confirmation of the results obtained in this work. It shows that in these kinds of stars, the [Fe/H] determination might be affected by variability. Furthermore, it provides us with the possibility that the physical reason for the variability of our stars is some kind of pulsation.

Because of that, we suggest that if the variability is due to pulsations, the [Fe/H] spread difference between variable and nonvariable stars could originate from the fact that the standard technique for chemical analysis uses hydrostatic LTE atmospheric models, while pulsating stars have by definition nonhydrostatic atmospheres. Hydrostatic LTE models work because they resemble real atmospheres where, in most of the cases, the gas is static on a large scale and the gas dense enough to allow the light coming from the deepest part of the photosphere to be fully absorbed and reprocessed by the different atmospheric layers before leaving the stellar surface. This means that each layer behaves like a blackbody, and for this reason, it can be treated by the LTE approximation. This is not strictly true for the spectral lines formed at the top of the photosphere, but it works for most of the lines that are formed in the deeper parts of the atmosphere. In pulsating stars, the atmosphere is expanding and contracting radially or tangentially, and during the expansion, the gas becomes less dense and so its behavior deviates from the LTE approximation. Also, the pulsation itself could have a direct impact on the spectroscopic [Fe/H] determination in the sense that it could alter the atmospheric structure and specifically how temperature and pressure vary with optical depth. Because these variables are assumed to vary as it is predicted in the atmospheric model, a mismatch between the predicted and real atmospheric structure can easily lead to an underestimation or overestimation of the iron content.

Table 6
Mean, σ, and Errv of the Iron Abundances for Each Group of Stars

| Classification | \( \bar{\chi} \) (dex) | σ (dex) | \( \sigma \) (dex) | \( \text{Err}_v \) (dex) |
|----------------|---------------------|--------|-----------------|-----------------|
| [Fe I/H]_{Mucciarelli} Variable | −1.46 | 0.04 | 0.12 | 0.03 |
| Possible | −1.50 | 0.03 | 0.05 | 0.02 |
| Nonvariable | −1.48 | 0.02 | 0.06 | 0.01 |
| [Fe II/H]_{Mucciarelli} Variable | −1.37 | 0.02 | 0.06 | 0.01 |
| Possible | −1.41 | 0.03 | 0.04 | 0.02 |
| Nonvariable | −1.43 | 0.01 | 0.02 | 0.01 |
| [Fe/H]_{Simmerer} Variable | −1.56 | 0.04 | 0.13 | 0.03 |
| Possible | −1.55 | 0.04 | 0.04 | 0.02 |
| Nonvariable | −1.53 | 0.03 | 0.08 | 0.02 |

Figure 14. Plot displaying the midphase in the x-axis and the [Fe I/H]_{Star} − ⟨[Fe I/H]_{Star}⟩ in the y-axis for the 11 different RR Lyrae stars from For et al. (2011).
stars in GCs as obtained from the spectra using standard techniques. We performed the GLS and the PDM methods along with a set of discarding criteria in order to check for variables. Of the total sample of 17 giant stars, 8 targets were classified as variable stars, 2 as possible variables, and 7 as nonvariables.

After obtaining the main parameters (period $P$ and amplitude $A$) of the eight variable stars for both the $V$ and $I$ filters, we revised the results from Mucciarelli et al. (2015) regarding their iron abundance. We also analyzed our variable stars according to their period, amplitude, position in the CMD, and the shape of the LC, comparing them with known variables, concluding that the most probable reason for the variability is radial or tangential pulsation. We also revised the results from Simmerer et al. (2013) to see if there is some difference depending on the different methods used to obtain the metallicity. We conclude that the most probable reason for the variability is radial or tangential pulsation. We also revised the results from Simmerer et al. (2013) to see if there is some difference depending on the different methods used to obtain the metallicity. We conclude that the most probable reason for the variability is radial or tangential pulsation.

More concentrated around the mean value of the cluster means that variable stars can display extreme values of metallicity (both toward metal-richer and metal-poorer ends), while stars that do not present variability display values of their iron abundance closer to the mean abundance of the total sample. Furthermore, this finding is consistent with the metal-poor variable RGB star found in Muñoz et al. (2018). More data for both photometric and spectroscopic analysis are needed in order to further confirm our results, but nevertheless, this is a step forward to determine the nature of the variable star and its influence on metallicity. Finally, our result suggests that the spectroscopic determination of the iron abundance of giant stars in NGC 3201 is affected in some way by the variability of such stars and point toward the fact that this cluster does not have an intrinsic iron spread.

S.V. gratefully acknowledges the support provided by Fondecyt reg. n. 1170518. This work is based on data acquired at Complejo Astronómico El Leoncito, operated under agreement between the Consejo Nacional de Investigaciones Científicas y Técnicas de la República Argentina and the National Universities of La Plata, Córdoba, and San Juan. Furthermore, this work made use of the PyAstronomy package collection, and we are thankful to the PyA group for answering our doubts regarding their packages. Finally, the authors gratefully acknowledge the comments and suggestions of the anonymous referee that greatly improved and strengthen this paper.

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