Discovery of a Large Population of Nitrogen-enhanced Stars in the Magellanic Clouds

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Abstract

We report the APOGEE-2S+ discovery of a unique collection of nitrogen-enhanced mildly metal-poor giant stars, peaking at [Fe/H] ~ −0.89 with no carbon enrichment, toward the Small and Large Magellanic Clouds (SMC and LMC), with abundances of light- (C, N), odd-Z (Al, K), and α-elements (O, Mg, Si) that are typically found in Galactic globular clusters (GCs). Here we present 44 stars in the SMC and LMC that exhibit significantly enhanced [N/Fe] abundance ratios, well above ([N/Fe] ≥ +0.6) typical Galactic levels at similar metallicity, and a star that is very nitrogen-enhanced ([N/Fe] > +2.45). Our sample consists of luminous evolved stars on the asymptotic giant branch (AGB), eight of which are classified as bona fide semi-regular (SR) variables, as well as low-luminozity stars similar to those of stars on the tip of the red giant branch of stellar clusters in the SMC and LMC. It seems likely that whatever nucleosynthetic process is responsible for these anomalous SMC and LMC stars is similar to that which caused the common stellar populations in GCs. We interpret these distinctive C−N patterns as observational evidence of the result of tidally shredded GCs in the SMC and LMC. These findings might explain some previous conflicting results over bulge N-rich stars, and broadly help to understand GC formation and evolution. Furthermore, the discovery of such a large population of N-rich AGB stars in the SMC and LMC suggests that multiple stellar populations might not only be exotic events from the past, but can also form at lower redshift.

Unified Astronomy Thesaurus concepts: Asymptotic giant branch stars (2100); Chemically peculiar stars (226); Stellar abundances (1577); Globular star clusters (656); Large Magellanic Cloud (903); Small Magellanic Cloud (1468); Red giant branch (1368); Semi-regular variable stars (1444)

1. Introduction

It has been well established that some metal-poor (−2.0 < [Fe/H] < −0.7) stars within the Milky Way may produce a [N/Fe] overabundance (i.e., N-rich stars; Bessell & Norris 1982; Beveridge & Sneden 1994; Johnson et al. 2007; Fernández-Trincado et al. 2016, 2017, 2019b, 2019a, 2019c, 2020; Martell et al. 2016; Schiavon et al. 2017) that replicates or exceeds the chemical patterns seen in the so-called second-generation (Fernández-Trincado et al. 2019d; Mészáros et al. 1641), and as such we would expect to find similar chemical signatures in the Large Magellanic Cloud (LMC), which also has a halo (Minniti et al. 2003; Borissova et al. 2006). On the contrary, for metal-poor field stars with metallicities down to [Fe/H] = −0.7, the [N/Fe] ratio is not higher than +0.5.

Galactic GCs are expected to lose mass through processes like evaporation and tidal stripping (e.g., Baumgardt & Makino 2003), and the favored hypothesis for the origin of the N-rich stars is that they were once part of a GC. This conjecture appears to be well supported by the chemokinematics similarity between a number of nitrogen-enriched MW field stars and their possible GC progenitors (see, e.g., Martell et al. 2016; Tang et al. 2020; Fernández-Trincado et al. 2019b, 2020). Alternatively, it has been suggested that such a N-rich population could include the oldest stars in the MW, which could have been born in high-density environments (Chiappini et al. 2011; Bekki 2019).

The N-rich population is often typified by larger N overabundances, accompanied by decreased abundances of carbon ([C/Fe] ≲ +0.15) and α-elements (O and Mg). Sometimes they exhibit atmospheres extremely enriched in aluminum ([Al/Fe] ≳ +0.5) and s-process elements, suggesting that some of them could be objects in the AGB evolutionary stages that have undergone hot bottom burning (see, e.g., Fernández-Trincado et al. 2016, 2017, 2019b; Pereira et al. 2017), including a few cases that became strongly enriched in carbon.
phosphorus (see, e.g., Masseron et al. 2020), which could be biased toward red giant branch (RGB) stars in previous studies (Schiavon et al. 2017), or could be objects chemically enriched by an AGB companion (e.g., Cordero et al. 2015; Fernández-Trincado et al. 2019c).

The existence of N-rich stars in specific environments has proven to have important implications in the chemical makeup of multiple populations (MPs) in the context of GC evolution across a wide range of metallicity (see, e.g., Renzini et al. 2015; Fernández-Trincado et al. 2019d; Mészáros et al. 1641). Establishing whether N-rich stars in the MW and/or nearby Local Group systems formed in a GC could either reveal that MPs can also form, to some extent, in lower-density environments (e.g., Savino & Posti 2019), as well as provide important insights on the assembly history of their host systems, in particular on the role of GC disruption.

While the abundance properties of N-rich stars have been limited to GC stars and the inner/outerior (up to ≤100 kpc) stellar halo (Martell et al. 2016; Fernández-Trincado et al. 2017, 2019b, 2019a) and widely explored, little is known of these stars in nearby dwarf galaxies that surround the MW, even though some attempts to search for dissolved GCs in these systems via the investigation of chemical anomalies have been tried (e.g., Lardo et al. 2016).

The Apache Point Observatory Galactic Evolution Environment (APOGEE; Majewski et al. 2017) is currently obtaining near-IR spectra for stars in the Small Magellanic Cloud (SMC) and LMC (Nidever et al. 2020), providing us with an excellent window to examine the presence of disrupted GCs in nearby Local Group galaxies. In this Letter, we report the discovery of a large population of N-rich stars likely associated with GC dissolution and/or evaporation in the SMC and LMC. To our knowledge, none of the large spectroscopic surveys of the SMC and LMC system have so far included measurements of nitrogen abundances.

This work is organized as follows. In Section 2, we discuss the data and selection criteria employed to create the parent stellar sample used throughout the Letter. We present our analysis and conclusions in Section 3.

2. Data

In this work, we manually reexamined the high-resolution (R ∼ 22,500) spectra in the H band (λ ∼ 1.5–1.7 μm) from the APOGEE instrument (Gunn et al. 2006; Wilson et al. 2019) that operates on the Irénée Du Pont 2.5 m telescope (Bowen & Vaughan 1973) at Las Campanas Observatory (LCO; APOGEE-2S) as part of the incremental 16th data release of SDSS-IV (Blanton et al. 2017; Ahumada et al. 2020). These spectra include internal data through 2020 March from the APOGEE-2 survey (hereafter APOGEE-2S; Majewski et al. 2017) toward the Southern Hemisphere. Targeting strategies for APOGEE-2 S+, data reduction of the spectra, determination of radial velocities, and atmospheric parameters are fully described in Holtzman et al. (2015), Nidever et al. (2015), García Pérez et al. (2016), and Zasowski et al. (2017). All the spectra analyzed in this work are in the following ranges: (i) S/N > 60 pixel^{-1}; (ii) 3200 K < T_{eff} < 5500 K, −0.5 < log g < 5.5; (iii) ASPCAPFLAG==0.

We identified potential GC debris over ∼3535 mildly metal-poor (−2.0 < [Fe/H] < −0.7) stars toward the SMC and LMC in the [N/Fe]−[Fe/H] plane following the same methodology as described in Fernández-Trincado et al. (2019b). This yielded the serendipitous discovery of 44 stars toward the SMC and LMC with stellar atmosphere strongly enriched in nitrogen, which are typically found among the so-called second-generation of stars in Galactic GCs. The newly identified N-rich stars are shown as filled lime green dots in Figure 1.

Although a handful of N-rich star candidates have been identified in the APOGEE survey toward the inner halo (Martell et al. 2016) and Galactic Bulge (Schiavon et al. 2017), based on the ASPCAP/APOGEE DR12 catalog, the ASPCAP pipeline (García Pérez et al. 2016) contains some caveats that hamper a profound exploration and characterization of the mildly metal-poor N-rich population (for a review, see Fernández-Trincado et al. 2019b).

Here, we perform a spectral synthesis analysis, independently of the ASPCAP pipeline, to disentangle the underlying C, N, and O abundances from the 12C16O, 12C14N, and 16OH band strengths. To this purpose, we performed an LTE analysis with a MARCS grid of spherical models with the BACCHUS code (Masseron et al. 2016), adopting the same methodology as described in Fernández-Trincado et al. (2016, 2017, 2019b, 2019a, 2019c, 2019d). It is important to keep in mind that ASPCAP uses a global fit to the continuum in three detector chips independently, while we place the pseudo-continuum in a region around the lines of interest. We believe that our manual method is more reliable, since it avoids possible shifts in the continuum location due to imperfections in the spectral subtraction along the full spectral range.

In order to provide a consistent chemical analysis, we redetermine the chemical abundances by means of a careful line selection, and measure abundances based on a line-by-line basis with the BACCHUS code, and by adopting the line selection for the various elements as in Fernández-Trincado et al. (2019b). Finally, we rederived chemical abundances adopting as input the uncalibrated effective temperatures (T_{eff}), surface gravities (log g_{ms}), and the overall metallicity ([M/Fe]) from the ASPCAP pipeline. We do not calculate chemical abundances based on the photometric atmospheric parameters, as they become error dominated for stars toward the SMC and LMC, due the difficulty of calculating accurate reddening in these regions (see, e.g., Nidever et al. 2020), making them unsuitable to estimate precise chemical abundances for stars in the inner SMC and LMC. The results are summarized in Table 1.

3. Results and Analysis

We find that the newly identified N-rich stars span a wide range of metallicities (−1.4 < [Fe/H] < −0.7), peaking at [Fe/H] ∼ −0.89, and that they exhibit nitrogen abundances well above typical Galactic levels over a range of metallicities, which is ≥3σ above the typical MW [N/Fe]. It seems likely that whatever nucleosynthesis process is responsible for these nitrogen overabundances in the field of the SMC and LMC is similar to that which caused the unusual stellar populations in Galactic GCs at similar metallicity.

Figures 1(a)–(d) reveal the existence of a large number of N-rich stars toward the SMC and LMC. There are 34 out of 44 N-rich stars located at the center of the SMC, whereas 10 stars in our sample reside on the periphery of the LMC.

Figures 2(a) and (d) show the proper motions of Gaia DR2, confirming that the N-rich stars are permanent residents of the SMC and LMC. In the case of N-rich stars in the SMC, it is
clearly visible that its proper motion distribution deviates by more than 4σ from the nominal proper motions of the NGC 104 and NGC 362 GCs. Figures 2(b) and (e) also reveal that the radial-velocity distributions differ from those of the field GCs, while the color–magnitude diagram (CMD) using Gaia bands (see Figures 2(c) and (f)) also rules out the possibility that these N-rich stars are stellar debris of these two Galactic GCs. This is also supported by inspection of [Fe/H]; the N-rich stars exhibit a larger metallicity scatter, on average being more metal-rich than NGC 362 and more metal-poor than NGC 104. Based on these properties, we conclude that these are bona fide N-rich stars in the SMC and LMC, which are chemically identical to those identified toward the bulge and halo of the MW (see, e.g., Fernández-Trincado et al. 2017, 2019b, 2019c, 2019d).

Figure 3 presents some of the light-, odd-Z, and α-element patterns, and demonstrates a very distinct separation in nitrogen, with a star-to-star scatter Δ[N/Fe] ≥ +0.28 dex and Δ[C/Fe] ≥ +0.25 dex, which is moderately anticorrelated with [C/Fe], and runs roughly between {[C/Fe], [N/Fe]} = {−0.6, +0.53} and {+0.15, +1.0}. We have found mean values for [C/Fe], [N/Fe], [O/Fe], [Mg/Fe], [Al/Fe], [Si/Fe], [K/Fe], [Ce/Fe], and [Nd/Fe] that are compatible with Galactic GC stars (Mészáros et al. 1641) at similar metallicity. There is also a star with [N/Fe] ≥ +2.42 that exceeds the extreme abundance patterns seen in Galactic GCs, highlighting the uniqueness of these stars. Overall, we can see clearly from Figure 3 that our sample of stars in the SMC and LMC behave in a similar way as MW GC stars, supporting the idea that most of the newly identified stars could be related to SMC and LMC GCs.

The newly identified N-rich population is separated relatively cleanly from MW stars and SMC and LMC stars in the [C/Fe] versus [N/Fe] and [N/Fe] versus [Al/Fe] planes. In general, these N-rich stars exhibit slightly higher abundance ratios in Al, Si, Ti, and Ni compared to the SMC and LMC populations, but they exhibit lower abundance ratios in O, Mg, Al, Si, K, and C compared to MW field stars, with the α-elements (O, Mg, Si, and Ca) at comparable levels (∼+0.1) to low-α halo MW field stars (e.g., Hayes et al. 2018).

The star-to-star scatter is between 0.1 and 0.3 dex for the different chemical species, being slightly lower for the α-elements. Therefore, the star-to-star scatter in iron and other chemical species could be attributed to different progenitors, which could explain the observed chemical anomalies toward the SMC and LMC, in a similar manner as observed in and around the MW halo metal-poor stars today. The mildly metal-poor N-rich stars toward the SMC and LMC may have formed following minor merger events in the early history of the SMC and LMC. However, there are other observational features in our sample that allow us to invoke other possible scenarios to explain the observed abundance patterns toward the SMC and LMC.

Our sample includes five semi-regular (SR) variable stars reported in the ASAS-SN Catalog of Variable Stars.
### Table 1

**Basic Parameters and Abundances of the SMC and LMC N-rich Stars**

| Target Id  | RA (J2000) | Dec (J2000) | log g | T_eff | [M/H] | [C/Fe] | [N/Fe] | [O/Fe] | [Mg/Fe] | [Al/Fe] | [S/Fe] | [Ca/Fe] | [Ti/Fe] | [P/Fe] | [V/Fe] |
|------------|-------------|-------------|-------|-------|-------|--------|--------|--------|--------|--------|-------|--------|--------|-------|-------|
| 2M01545497 | 84.37       | -72.00      | 2.50  | -0.93 | +0.09 | +0.69  | +0.21  | +0.17  | -0.24  | +0.24  | +0.01 | +0.07  | +0.19  | -0.94 | -0.09 |
| 2M01522260 | 84.37       | -72.00      | 2.50  | -0.93 | +0.09 | +0.69  | +0.21  | +0.17  | -0.24  | +0.24  | +0.01 | +0.07  | +0.19  | -0.94 | -0.09 |
| 2M01511944 | 84.37       | -72.00      | 2.50  | -0.93 | +0.09 | +0.69  | +0.21  | +0.17  | -0.24  | +0.24  | +0.01 | +0.07  | +0.19  | -0.94 | -0.09 |
| 2M01573127 | 84.37       | -72.00      | 2.50  | -0.93 | +0.09 | +0.69  | +0.21  | +0.17  | -0.24  | +0.24  | +0.01 | +0.07  | +0.19  | -0.94 | -0.09 |
| 2M01641341 | 84.37       | -72.00      | 2.50  | -0.93 | +0.09 | +0.69  | +0.21  | +0.17  | -0.24  | +0.24  | +0.01 | +0.07  | +0.19  | -0.94 | -0.09 |
| 2M01653396 | 84.37       | -72.00      | 2.50  | -0.93 | +0.09 | +0.69  | +0.21  | +0.17  | -0.24  | +0.24  | +0.01 | +0.07  | +0.19  | -0.94 | -0.09 |
| 2M01641341 | 84.37       | -72.00      | 2.50  | -0.93 | +0.09 | +0.69  | +0.21  | +0.17  | -0.24  | +0.24  | +0.01 | +0.07  | +0.19  | -0.94 | -0.09 |
| 2M01653396 | 84.37       | -72.00      | 2.50  | -0.93 | +0.09 | +0.69  | +0.21  | +0.17  | -0.24  | +0.24  | +0.01 | +0.07  | +0.19  | -0.94 | -0.09 |
| 2M01653396 | 84.37       | -72.00      | 2.50  | -0.93 | +0.09 | +0.69  | +0.21  | +0.17  | -0.24  | +0.24  | +0.01 | +0.07  | +0.19  | -0.94 | -0.09 |
| 2M01653396 | 84.37       | -72.00      | 2.50  | -0.93 | +0.09 | +0.69  | +0.21  | +0.17  | -0.24  | +0.24  | +0.01 | +0.07  | +0.19  | -0.94 | -0.09 |
| 2M01653396 | 84.37       | -72.00      | 2.50  | -0.93 | +0.09 | +0.69  | +0.21  | +0.17  | -0.24  | +0.24  | +0.01 | +0.07  | +0.19  | -0.94 | -0.09 |
| 2M01653396 | 84.37       | -72.00      | 2.50  | -0.93 | +0.09 | +0.69  | +0.21  | +0.17  | -0.24  | +0.24  | +0.01 | +0.07  | +0.19  | -0.94 | -0.09 |
| 2M01653396 | 84.37       | -72.00      | 2.50  | -0.93 | +0.09 | +0.69  | +0.21  | +0.17  | -0.24  | +0.24  | +0.01 | +0.07  | +0.19  | -0.94 | -0.09 |
| 2M01653396 | 84.37       | -72.00      | 2.50  | -0.93 | +0.09 | +0.69  | +0.21  | +0.17  | -0.24  | +0.24  | +0.01 | +0.07  | +0.19  | -0.94 | -0.09 |
| 2M01653396 | 84.37       | -72.00      | 2.50  | -0.93 | +0.09 | +0.69  | +0.21  | +0.17  | -0.24  | +0.24  | +0.01 | +0.07  | +0.19  | -0.94 | -0.09 |
| 2M01653396 | 84.37       | -72.00      | 2.50  | -0.93 | +0.09 | +0.69  | +0.21  | +0.17  | -0.24  | +0.24  | +0.01 | +0.07  | +0.19  | -0.94 | -0.09 |
| 2M01653396 | 84.37       | -72.00      | 2.50  | -0.93 | +0.09 | +0.69  | +0.21  | +0.17  | -0.24  | +0.24  | +0.01 | +0.07  | +0.19  | -0.94 | -0.09 |
| 2M01653396 | 84.37       | -72.00      | 2.50  | -0.93 | +0.09 | +0.69  | +0.21  | +0.17  | -0.24  | +0.24  | +0.01 | +0.07  | +0.19  | -0.94 | -0.09 |
| 2M01653396 | 84.37       | -72.00      | 2.50  | -0.93 | +0.09 | +0.69  | +0.21  | +0.17  | -0.24  | +0.24  | +0.01 | +0.07  | +0.19  | -0.94 | -0.09 |
| APOGEE–ID | Target Class | G-band (mag) | #Visits | S/N (pixel$^{-1}$) | RV (km s$^{-1}$) | oRV (km s$^{-1}$) | $T_{eff}$ (K) | log g (dex) | $\zeta$ (km s$^{-1}$) | [M/Fe] | [C/Fe] | [N/Fe] | [O/Fe] | [Mg/Fe] | [Al/Fe] | [Si/Fe] | [K/Fe] | [Ca/Fe] | [Ti/Fe] | [Fe/H] | [Ni/Fe] | [Cu/Fe] | [Nd/Fe] | [Yb/Fe] |
|-----------|-------------|------------|---------|-----------------|----------------|----------------|-------------|-----------|----------------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|
| 2M00505642 | SMC/... | 13.73 | 1 | 130 | 177.7 | ... | 3755 | 0.05 | 2.97 | −0.70 | −0.16 | +0.56 | +0.13 | +0.34 | −0.22 | +0.17 | −0.00 | +0.20 | +0.20 | −0.87 | −0.01 | +0.24 | ... | 0.72 |
| 7317378 | −7241586 | 2M0101550 | SMC/... | 13.67 | 1 | 137 | 133.4 | ... | 3788 | 0.08 | 2.78 | −0.69 | −0.31 | +0.66 | +0.04 | +0.07 | −0.25 | +0.12 | −0.02 | +0.11 | +0.04 | −0.74 | −0.07 | +0.36 | +0.79 | +0.61 |
| −7339480 | 2M0110557 | SMC/... | 14.53 | 2 | 150 | 154.7 | 0.0 | 3726 | 0.11 | 2.99 | −0.88 | −0.54 | +0.75 | +0.11 | +0.18 | −0.31 | −0.04 | −0.03 | +0.03 | +0.00 | −0.83 | −0.07 | +0.17 | +0.23 | ... | |
| −7326490 | 2M01623078 | SMC/... | 13.78 | 1 | 131 | 124.3 | ... | 3692 | 0.12 | 2.82 | −0.84 | −0.25 | +0.58 | +0.12 | +0.07 | −0.17 | +0.09 | −0.08 | +0.08 | +0.03 | −0.82 | −0.07 | +0.27 | +0.67 | ... | |
| −7203288 | 2M0102419 | SMC/... | 12.79 | 1 | 195 | 119.4 | ... | 3866 | 0.13 | 2.76 | −0.77 | −0.31 | +0.68 | +0.06 | +0.16 | −0.27 | +0.08 | −0.07 | +0.05 | +0.10 | −0.86 | −0.11 | −0.36 | ... | +0.65 |
| 7208498 | 2M0045676 | SMC/... | 13.26 | 1 | 153 | 128.4 | ... | 3952 | 0.18 | 2.82 | −0.74 | −0.34 | +0.57 | −0.04 | +0.05 | −0.32 | +0.07 | −0.11 | +0.01 | −0.05 | −0.71 | −0.16 | +0.34 | +0.62 | ... | |
| −7304450 | 2M01011946 | SMC/... | 12.70 | 1 | 193 | 155.3 | ... | 3980 | 0.21 | 2.89 | −0.88 | −0.47 | +0.58 | +0.00 | +0.06 | −0.31 | +0.11 | −0.10 | +0.03 | −0.07 | −0.80 | −0.13 | +0.28 | +0.66 | +0.88 |
| 7206485 | 2M01122821 | SMC/... | 14.24 | 2 | 151 | 194.2 | 0.1 | 3816 | 0.22 | 2.88 | −0.81 | −0.17 | +0.54 | +0.13 | +0.22 | −0.21 | +0.07 | −0.02 | +0.11 | +0.09 | −0.91 | −0.08 | +0.30 | +0.50 | +0.75 |
| −7302283 | 2M01115889 | SMC/... | 14.39 | 2 | 137 | 171.7 | 0.3 | 3855 | 0.28 | 2.94 | −0.74 | −0.32 | +0.65 | +0.10 | +0.11 | −0.34 | +0.07 | −0.04 | +0.12 | +0.05 | −0.76 | −0.02 | ... | +0.44 | +0.53 |
| 7318168 | 2M0051061 | SMC/... | 13.05 | 1 | 134 | 138.5 | ... | 3989 | 0.37 | 2.80 | −0.95 | −0.56 | +0.63 | +0.01 | −0.05 | −0.35 | +0.17 | −0.26 | +0.01 | +0.10 | −0.81 | −0.15 | −0.43 | +0.66 | +0.76 |
| −7363735 | 2M05082025 | SMC/... | 13.53 | 1 | 105 | 125.4 | ... | 3835 | 0.39 | 2.94 | −0.73 | −0.30 | +0.61 | +0.04 | +0.04 | −0.27 | +0.06 | −0.07 | +0.05 | +0.03 | −0.72 | −0.04 | +0.35 | +0.75 | +0.38 |
| 7135564 | 2M05237564 | SMC/... | 12.67 | 1 | 169 | 129.8 | ... | 4184 | 0.45 | 2.89 | −0.82 | −0.43 | +0.71 | −0.02 | −0.05 | −0.34 | +0.07 | −0.17 | +0.05 | +0.15 | −0.78 | −0.18 | −0.37 | ... | ... |
| −7251053 | 2M01093482 | SMC/... | 13.69 | 2 | 150 | 177.1 | 0.2 | 4009 | 0.51 | 2.95 | −0.85 | −0.30 | +0.56 | +0.06 | +0.10 | −0.26 | +0.15 | −0.11 | +0.02 | +0.01 | −0.82 | −0.04 | ... | +0.35 | +0.84 |
| −7239422 | 2M0573246 | SMC/... | 13.44 | 1 | 144 | 158.3 | ... | 4133 | 0.75 | 2.97 | −0.83 | −0.28 | +0.64 | +0.06 | +0.04 | −0.41 | +0.18 | −0.27 | +0.07 | −0.12 | −0.71 | −0.20 | ... | +1.58 | +0.96 |
| −7206024 | 2M0540589 | SMC/... | 13.63 | 1 | 149 | 116.8 | ... | 4047 | 0.83 | 2.88 | −0.79 | −0.41 | +0.66 | +0.05 | −0.02 | −0.36 | +0.12 | −0.20 | −0.00 | +0.13 | −0.71 | −0.06 | +0.19 | +0.72 | +0.90 |
Four of them are located toward the SMC, with one selected as a possible O-rich AGB star based on its position in the (J-Ks, H) diagram (see Nidever et al. 2020). We also identified an SR variable in our sample toward the LMC, selected as a bright RGB in Nidever et al. (2020). These SR stars have periods between $\sim$85 and 757 days and variability amplitudes between 0.17 and 0.51 mag in the $V$ band. In conclusion, we find evidence that the SR stars are neither carbon-rich nor oxygen-rich, but exhibit lower carbon and oxygen abundance ratios, $[C/Fe] < +0.15$ and $[O/Fe] \leq +0.23$. It is worth mentioning that no bias or uncertainties are introduced in our spectroscopic analysis, as is the case for, e.g., shorter-period Cepheids or RR Lyrae stars (Pancino et al. 2015).

Thus, the observed nitrogen abundances and the modest enhancements of the $s$-process elements, coupled with the apparent variability of these SR stars, suggest that some of the evolved objects could be likely intermediate-mass ($\sim$3–5 $M_\odot$) AGB stars (one of the likely agents that self-enriches the GCs) that have undergone hot bottom burning and are becoming N-rich, according to chemical evolution models (Karakaş et al. 2018), but without production of significant amounts of aluminum, as envisioned by Ventura et al. (2016). These SR N-rich stars have remarkably stronger $^{12}$C$^{14}$N lines (see Figure 4) compared to other stars with similar relevant parameters; it can be asserted that these have much higher nitrogen abundances. The presence of such young, mildly metal-poor stellar populations in the SMC and LMC has important implications. Thus, the interpretation of our results depends crucially on establishing the evolutionary stage of the stars under analysis. It is also important to note that there are no known SMC and LMC GCs within an angular separation of approximately 1′ of these stars.

In this context, one can immediately notice that two subsamples occupy different loci in the CMD displayed in Figures 2(c) and (f). N-rich stars with $G \leq 15.0$ (LMC) and $G \leq 15.5$ (SMC) occupy the same locus as SMC and LMC AGB stars (referred to as “N-rich AGB” stars henceforth), while the N-rich stars with fainter $G$ magnitudes roughly occupy the same locus as the bright RGB stars in the SMC and LMC stellar clusters. These stars are tagged as genuine migrants from SMC and LMC GCs (hereafter N-rich BrRGB stars), and are among the oldest objects in the SMC and LMC. The existence of N-rich AGB stars in our sample can be also further assessed by the possible presence of circumstellar dust (Habing 1996), as the N-rich AGB stars occupy a locus toward colors that are redder than those N-rich BrRGB stars in the CMD diagram. In particular, 55% of the N-rich stars in our sample inhabit the AGB part of the diagram, which provides further evidence for an important contribution of AGB stars to our N-rich sample.
Although these stars have elemental abundances consistent with each other, we find that in the N-rich AGB stars the oxygen abundance ratios—generally lower than the $[\text{O}/\text{Fe}]$ of N-rich BrRGB stars—this lends further support to the notion that the two populations do not share the same origin.

It is also interesting to note that all the N-rich AGB stars in our sample were identified toward the SMC system, while the N-rich BrRGB stars are present in both, and likely could be part of the oldest stars in the SMC and LMC. We also conclude that there is significant evidence for a large contribution of possible AGB stars to our sample toward the SMC and LMC, suggesting that the detection of N-rich stars toward the MW has been biased toward RGB stars (e.g., Schiavon et al. 2017), which should result in a substantial difference in AGB contribution to the N-rich sample and the rest of the field, as already noted in Fernández-Trincado et al. (2019b).

Our finding can be understood in terms of different scenarios. Here, we conjecture that there may be at least two possible channels for the production of N-rich stars in the SMC and LMC: (i) The N-rich BrRGB stars could be former members of a population of GCs that was previously dissolved and/or evaporated in the SMC and LMC, and were later incorporated into the field of the SMC and LMC themselves—“smoking gun” evidence that they have been accreted along with their now-disrupted host GCs. Such a scenario could potentially explain the predominance of N-rich BrRGB stars that are currently not gravitationally bound to any SMC and LMC clusters. The chemical patterns of these stars are identical or comparable to those seen in old MW GC stars (e.g., Mészáros et al. 1641), and possibly associated with SMC and LMC GCs, with ages between $\sim 2$ and 10 Gyr (Hollyhead et al. 2018; Lagioia et al. 2019; Milone et al. 2020). In support of this scenario, one would expect to find N-rich BrRGB stars in the same environments as GCs today, as at least some of them would have been formed in the same molecular clouds as the GCs themselves. Thus, this observational finding would suggest that either some old GCs in the SMC and LMC have possibly experienced significant stellar mass-loss (e.g., Mackey et al. 2007; Dalessandro et al. 2016). This would suggest a common, single pathway for the formation and evolution of old ($\gtrsim 2$ Gyr) GCs within the Local Group (Martocchia et al. 2017). (ii) On the other hand, the discovery of a significant population of N-rich stars in the AGB evolutionary stage (and possibly of intermediate mass) further supports the idea that AGB stars are possibly one of the key players in the pollution of the intracluster medium (e.g., Ventura et al. 2016) proposed to explain the formation of MPs in GCs.
The presence of such a significant young and moderately metal-poor stellar populations in the SMC and LMC would have interesting consequences for the understanding of the formation and evolution of GC systems in the local universe, i.e., the presence of star-to-star abundance spreading in this possible “young” N-rich AGB population appears to be at odds with the apparent near-exclusivity of this population within old GCs.

Figure 4. High-resolution near-IR H-band spectrum of the newly identified N-rich stars in the SMC (left) and LMC (right), covering spectral regions around the $^{12}\text{C}^{14}\text{N}$ band (orange squares). Superimposed is the best fit of a MARCS/BACCHUS spectral synthesis (black line). The legends in each panel show the absolute abundance, $A(N)$, and the signal-to-noise ($S/N$) in the region of the feature, respectively.
4. Concluding Remarks

We report the serendipitous discovery of a large population of mildly metal-poor N-rich stars toward the SMC and LMC. Our sample is composed mainly of stars in the bright RGB (45%) and AGB (55%) evolutionary stage. This sample adds to the literature nitrogen measurements for several new stars; to our knowledge, none of the large spectroscopic surveys of the SMC and LMC have so far included measurements of significant nitrogen abundances.

The discovery of two subpopulations of N-rich stars suggests that the occurrence of chemical anomalies (also crucial in the chemical makeup of MPs in all GCs) might not be exotic events from the past, but can also form at lower redshift, as also envisaged by Bekki (2019), and not limited to stars with masses less than ~1.6 M_☉ (see, e.g., Bastian & Lardo 2018).

Our findings motivate the future search for N-rich stars in Local Group dwarf galaxies that could have once hosted GCs, now in the form of disrupted remnants. Light-element variations have, however, not been found among the dwarf’s field stars (Geisler et al. 2007; Villanova et al. 2017).

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References

Ahumada, R., Prieto, C. A., Almeida, A., et al. 2020, ApJS, 249, 3
Bastian, N., & Lardo, C. 2018, ARA&A, 56, 83
Baumgardt, H., & Makino, J. 2003, MNRAS, 340, 227
Bekki, K. 2019, MNRAS, 490, 4007
Bessell, M. S., & Norris, J. 1982, ApJL, 263, L29
Beveridge, R. C., & Sneden, C. 1994, AJ, 108, 285
Bica, E. L. D., & Schmitt, H. R. 1995, ApJS, 101, 41
Blanton, M. R., Bershady, M. A., Abolfathi, B., et al. 2017, AJ, 154, 28
Borissova, J., Minniti, D., Rejkuba, M., & Alves, D. 2006, A&A, 460, 459
Browen, I. S., & Vaughan, A. H. J. 1973, ApOpt, 12, 1430
Chiappini, C., Frischknecht, U., Meynet, G., et al. 2011, Natur, 472, 454
Cordero, M. J., Hansen, C. J., Johnson, C. I., & Pilachowski, C. A. 2015, ApJL, 808, L10
Dalessandro, E., Lapenna, E., Mucciarelli, A., et al. 2016, ApJ, 829, 77
Fernández-Trincado, J. G., Beers, T. C., Placco, V. M., et al. 2019a, ApJL, 886, L8
Fernández-Trincado, J. G., Beers, T. C., Tang, B., et al. 2019b, MNRAS, 488, 2864
Fernández-Trincado, J. G., Chaves-Velasquez, L., Pérez-Villegas, A., et al. 2020, MNRAS, 495, 4113
Fernández-Trincado, J. G., Mennickent, R., Cabezas, M., et al. 2019c, A&A, 631, A97
Fernández-Trincado, J. G., Robin, A. C., Moreno, E., et al. 2016, ApJ, 833, 132
Fernández-Trincado, J. G., Zamora, O., García-Hernández, D. A., et al. 2017, ApJL, 846, L2
Fernández-Trincado, J. G., Zamora, O., Souto, D., et al. 2019d, A&A, 627, A178
Gaia Collaboration, Helmi, A., van Leeuwen, F., et al. 2018, A&A, 616, A12
García Pérez, A. E., Allende Prieto, C., Holtzman, J. A., et al. 2016, AJ, 151, 144
Geisler, D., Wallerstein, G., Smith, V. V., & Casetti-Dinescu, D. I. 2007, PASP, 119, 939
Gunn, J. E., Siegmund, W. A., Mannery, E. J., et al. 2006, AJ, 131, 2332
Habing, H. J. 1996, A&ARv, 7, 97
Hayes, C. R., Majewski, S. R., Shetrone, M., et al. 2018, ApJ, 852, 49
Hollyhead, K., Lardo, C., Kacharov, N., et al. 2018, MNRAS, 476, 114
Holtzman, J. A., Shetrone, M., Johnson, J. A., et al. 2015, AJ, 150, 148
Jayeasinghe, T., Kochanek, C. S., Stanek, K. Z., et al. 2020, arXiv:2006.10057
Johnson, J. A., Herwig, F., Beers, T. C., & Christlieb, N. 2007, ApJ, 658, 1203
Karaka, A. I., Lugaro, M., Carlos, M., et al. 2018, MNRAS, 477, 421
Lagioia, E. P., Milone, A. P., Marino, A. F., & Dotter, A. 2019, ApJ, 871, 140
Lardo, C., Battaglia, G., Pancino, E., et al. 2016, A&A, 585, A70

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Mackey, A. D., Wilkinson, M. I., Davies, M. B., & Gilmore, G. F. 2007, MNRAS, 379, L40
Majewski, S. R., Schiavon, R. P., Frinchaboy, P. M., et al. 2017, AJ, 154, 94
Martell, S. L., Shetrone, M. D., Lucatello, S., et al. 2016, ApJ, 825, 146
Martocchia, S., Bastian, N., Usher, C., et al. 2017, MNRAS, 468, 3150
Masseron, T., García-Hernández, D. A., Santoveña, R., et al. 2020, NatCo, 11, 3759
Masseron, T., Merle, T., & Hawkins, K. 2016, BACCHUS: Brussels Automatic Code for Characterizing High accuracy Spectra, Astrophysics Source Code Library, ascl:1605.004
Mészáros, S., Masseron, T., García-Hernández, D. A., et al. 2020, MNRAS, 492, 1641
Milone, A. P., Marino, A. F., Da Costa, G. S., et al. 2020, MNRAS, 491, 515
Minniti, D., Borissova, J., Rejkuba, M., et al. 2003, Sci, 301, 1508
Nidever, D. L., Hasselquist, S., Hayes, C. R., et al. 2020, ApJ, 895, 88
Nidever, D. L., Holtzman, J. A., Allende Prieto, C., et al. 2015, AJ, 150, 173
Palma, T., Gramajo, L. V., Claria, J. J., et al. 2016, A&A, 586, A41
Pancino, E., Britavskiy, N., Romano, D., et al. 2015, MNRAS, 447, 2404
Pereira, C. B., Smith, V. V., Drake, N. A., et al. 2017, MNRAS, 469, 774
Renzini, A., D’Antona, F., Cassisi, S., et al. 2015, MNRAS, 454, 4197
Savio, A., & Posti, L. 2019, A&A, 624, L9
Schiavon, R. P., Zamora, O., Carrera, R., et al. 2017, MNRAS, 465, 501
Tang, B., Fernández-Trincado, J. G., Liu, C., et al. 2020, ApJ, 891, 28
Ventura, P., García-Hernández, D. A., Dell’Agli, F., et al. 2016, ApJL, 831, L17
Villanova, S., Moni Bidin, C., Mauro, F., Munoz, C., & Monaco, L. 2017, MNRAS, 464, 2730
Wilson, M. L., Eastman, J. D., Cornachione, M. A., et al. 2019, PASP, 131, 115001
Zasowski, G., Cohen, R. E., Chojnowski, S. D., et al. 2017, AJ, 154, 198