On the Identification of N-rich Metal-poor Field Stars with Future Chinese Space Station Telescope (Postprint)

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Abstract

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Full Text

Preamble

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On the Identification of N-rich Metal-poor Field Stars with Future Chinese Space Station Telescope

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Abstract

During the long-term evolution of globular clusters (GCs), some member stars are lost to the field. The recently discovered nitrogen-rich (N-rich) metal-poor field stars are promising candidates for these GC escapees, since nitrogen enhancement is the fingerprint of chemically enhanced populations in GCs. In this work, we discuss the possibility of identifying N-rich metal-poor field stars with the upcoming Chinese Space Station Telescope (CSST). We focus on the main survey camera with NUV, u, g, r, i, z, y filters and a slitless spectrograph with resolution of about 200.

The combination of UV-sensitive equipment and prominent N-related molecular lines in the UV band bodes well for identification: the color–color diagram of (u − g) versus (g − r) is capable of separating N-rich field stars from normal halo stars, provided that metallicity can be estimated without using u-band photometry information. Furthermore, synthetic spectra show that a signal-to-noise ratio of 10 is sufficient to identify N-rich field stars. In the near future, a large sample of N-rich field stars found by CSST, combined with state-of-the-art N-body simulations, will be crucial to deciphering GC-Galaxy co-evolution.

Key words: stars: chemically peculiar –stars: abundances –techniques: photometric –techniques: spectroscopic

1. Introduction

Recent surveys of globular clusters (GCs) reveal that almost all exhibit the phenomenon of multiple stellar populations (MPs; Gratton et al. 2012; Schiavon et al. 2017a; Masseron et al. 2019; Nataf et al. 2019; Mészáros et al. 2020). A defining feature of MPs is chemical inhomogeneity among member stars, manifested as anti-correlations between nitrogen (N) and carbon (C), sodium (Na) and oxygen (O), or aluminum (Al) and magnesium (Mg). The community generally interprets this as evidence of different primordial populations, referring to "first generation" (FG) and "second generation" (SG) stars as primordial and enriched populations, respectively. Typical SG stars exhibit distinct chemical abundance patterns compared to normal field stars at a given metallicity, showing enhanced N, Na (and sometimes helium (He), Al, and silicon (Si)) but depleted C and O (and sometimes Mg). This unique chemical fingerprint makes SG stars particularly suitable for tracing the evolution of individual stars formed in GCs.

Due to dynamical evolution within GCs (including two-body relaxation and ejection) and tidal interaction with the Milky Way (MW), GC stars are lost to the field (e.g., Weatherford et al. 2023). Identifying these GC escapees in the field is crucial for evaluating different stellar escape mechanisms and estimating their contribution to the MW halo. While GC escapees may not retain their dynamical properties for long, their chemistry can be preserved throughout their lifetimes. Although FG stars are almost chemically identical to halo field stars, SG stars exhibit clearly distinguishable chemical features. Among the various chemical peculiarities mentioned above, nitrogen enrichment is the most economical to identify, thanks to CN molecular features that can be easily detected even in large spectroscopic surveys with spectral resolution as low as 1800.

Using low-resolution optical spectra from the SEGUE survey (Yanny et al. 2009) and high-resolution near-infrared spectra from the APOGEE survey (Majewski et al. 2017), numerous N-rich field stars have been discovered in the MW and its satellite galaxies (e.g., Martell & Grebel 2010; Martell et al. 2011, 2016; Schiavon et al. 2017b; Fernández-Trincado et al. 2020, 2021). Additionally, the LAMOST survey (Zhao et al. 2012), with its unprecedented number of stellar spectra, has joined this effort: Tang et al. (2019, 2020) found 100 N-rich metal-poor field stars, which were later confirmed to be chemically identical to GC member stars (Yu et al. 2021).

However, a much larger sample of N-rich field stars is required to fully evaluate their escape mechanisms and the contribution of GC escapees to the MW halo. In this regard, photometric surveys or spectroscopic surveys with lower spectral resolution could be more efficient for searching for N-rich field stars. The upcoming Chinese Space Station Telescope (CSST) will substantially increase the sample size of N-rich field stars. Its capability to obtain ultraviolet images and spectra makes it particularly well-suited for detecting N-enrichment, due to the presence of NH and CN molecular bands in the 300–450 nm wavelength range. The CSST is scheduled for launch around 2024 and will share an orbit with the Chinese space station. Its main survey module features a large field of view (1.1 square degrees) and high spatial resolution (0.15). The limiting magnitudes in the u and g bands are expected to reach 25.4 mag and 26.3 mag (AB magnitude), respectively, for point sources (Zhan 2021). The main survey module will obtain multi-band imaging data (NUV and ugrizy) and slitless spectra (R 200; Zhan 2021) across 17,500 square degrees of sky during its planned ten-year observation program. CSST also carries four additional instruments: Multi-channel Imaging (MCI), Integral Field Spectrograph (IFS), Cool Planet Imaging Coronagraph (CPIC), and Terahertz Receiver (THz). Li et al. (2022) demonstrated the possibility of disentangling stellar populations with different abundances of He, C, N, O, and Mg using MCI/CSST photometry. In this work, we estimate the capability of identifying N-rich field stars using photometry and slitless spectra from the main survey camera.

This paper is organized as follows. Section 2 introduces our methodology for generating a mock photometric catalog of MW halo stars that includes N-rich field stars. Section 3 assesses the feasibility of separating N-rich field stars from normal halo stars using color–color diagrams (from CSST main survey camera filters) and slitless spectra. Sections 4 and 5 present our discussions and conclusions, respectively.

2. Method

The logic behind identifying N-rich stars with UV-related photometry and spectroscopy lies in their strong NH and CN features in this wavelength range (Figure 1 [Figure 1: see original paper]). The u-band filter in the CSST main survey camera covers the NH3400 and CN3839 molecular lines, while the g-band filter covers the CN4142 and CH4300 molecular lines. The different profiles of these molecular lines caused by peculiar C and N abundances may produce noticeable changes in u-band or g-band magnitudes.

To estimate the feasibility of identifying N-rich stars under realistic conditions, this work employs the smooth halo catalog from the CSST Mock Catalog of Stellar Halo (J. Chang et al. 2023, in preparation). We use the GALAXIA software (Sharma et al. 2011), which is based on N-body simulations from Bullock & Boylan-Kolchin (2017), to generate a stellar halo of the MW. The stellar halo catalog includes six-dimensional kinematic parameters (positions and velocities), as well as information such as mass, age, metallicity, effective temperature, and luminosity for each star. Considering the CSST footprint, the stellar halo catalog only includes stars with galactic latitude of 25° or higher.

GALEVNB (Pang et al. 2016) is used to generate CSST photometric magnitudes based on these stellar parameters by convolving theoretical spectra with the CSST main camera filters. Consequently, the photometric catalog also includes magnitudes in the CSST main camera filters. In the previous catalog, we assumed a solar abundance pattern with [C/Fe] $= 0$ and [N/Fe] $= 0$ for all stars. However, non-solar chemical abundances (e.g., C and N) can change the depth of spectral features, which affects photometric magnitudes. To obtain magnitude differences between non-solar and solar chemical patterns, we generate corresponding synthetic spectra (R 200) and convolve them with the CSST main camera filters. We employ the publicly available tool ISPEC (Blanco-Cuaresma et al. 2014; Blanco-Cuaresma 2019) to generate synthetic spectra, using the radiative transfer code and line lists from SPECTRUM (Gray 1999), MARCS model atmospheres (Gustafsson et al. 2008), and solar abundances from Asplund et al. (2009). Finally, we add these magnitude differences to the photometric magnitudes from the aforementioned catalog to obtain a new catalog that incorporates non-solar chemical patterns.

3.1. Photometric Identification of N-rich Giant Stars

Since C and N abundances in giant stars may change substantially after they undergo first dredge-up and extra-mixing, we separate giants and dwarfs in our photometric identification of N-rich stars. Giant stars with log g < 3.0 were selected, while blue horizontal branch (BHB) stars were discarded from the Kiel diagram because high temperatures destroy C and N related molecules. Figure 2 [Figure 2: see original paper] shows the Kiel diagram, with color representing the number density of sample stars. Following the selection criteria and statistical results presented in Tang et al. (2020), we (1) limited the metallicity range of our sample stars to $-1.8 <$ [Fe/H] < -1.0, and (2) assumed that 1% of the sample stars are N-rich stars and 99% are normal stars.

To simulate stars with realistic C and N abundances, we set the chemical patterns of N-rich giants and normal giants as follows. For normal giants, we used red giant stars from Shetrone et al. (2019) as a reference and fitted correlations between C(N) abundances and surface gravity (Figure 3 [Figure 3: see original paper]), since C and N abundances change as a star climbs the red giant branch (RGB). For a star with a given surface gravity, we first estimated the expected values of C and N from the fitted correlations, then added a random error following a Gaussian distribution with $= 0$ dex and $\sigma = 0.2$ dex. For N-rich giants, the C abundance remains debated; here we follow the distribution of normal giants. For their N abundance, we follow the observational results of B. Tang et al. (2023, in preparation), setting the expected value to 1.2 dex with error also following a Gaussian distribution with $= 0$ dex and $\sigma = 0.2$ dex. We then generated new photometric magnitudes according to Section 2.

After exploring various color-magnitude and color-color diagrams using different combinations of CSST filters, we found that $u - g$ versus $g - r$ is a promising diagnostic color-color diagram for separating stars with different N enrichment, as we have shown that UV and blue filters are particularly sensitive to N enrichment (Figure 1). To maximize identification of N-rich stars, we divided the metallicity range $[-1.8, -1.0]$ into four bins of equal width. Figure 4 [Figure 4: see original paper] displays the results for the metallicity bin $[-1.2, -1.0]$;

color-color diagrams for other metallicity ranges can be found in Figure A1 in the Appendix. We rebinned the normal giant stars on g − r with a bin width of 0.04 mag and calculated their 100% quantile in u − g for each bin.

After obtaining the 100% quantile points for all g − r bins (red points in Figure 4), we fitted a fifth-order polynomial to these quantile points (red curve in Figure 4). The polynomial coefficients are listed in Table 1 . Stars on the left-hand side of the red curve should constitute a pure sample of N-rich giant stars. However, the real situation is slightly more complicated: the pollution rate (Table 1) is not zero because (1) we binned g − r with a step size of 0.04 mag, and (2) the red curve (polynomial fit) may not follow the red points exactly. We also calculated the hit probability (Table 1), defined as the ratio of identified N-rich stars (left of the red curve) to all N-rich stars.

According to Table 1, the hit probabilities are substantial for all metallicity bins, including the full metallicity range [−1.8, −1.0], suggesting that the u − g versus g − r color-color diagram can effectively separate N-rich stars from normal stars. Comparing hit probabilities across metallicity ranges reveals that bins with higher metallicity ([−1.2, −1.0] and [−1.4, −1.2]) show larger values due to stronger molecular features at higher metallicity. The hit probabilities for divided metallicity ranges exceed that for the full metallicity range, suggesting that subdividing the metallicity range can help select more N-rich giant stars.

3.2. Photometric Identification of N-rich Dwarf Stars

Due to the vast number of dwarf stars in our catalog, we randomly sampled 1% of the dwarf star sample (log g > 4.0, −1.8 < [Fe/H] < −1.0) to save computational time. Since the capability to identify N-rich stars is not affected by sample size once it reaches a statistically significant number, we consider our simplified dwarf star sample (10^6) sufficient for the following discussion. The Kiel diagram (Figure 5 [Figure 5: see original paper]) shows that our sample covers the expected Teff and log g parameter space. For N-rich dwarf stars (1% of our simplified sample), we set their [N/Fe] values to an expected value of 0.8 dex plus random error following a Gaussian distribution with = 0 dex and σ = 0.2 dex, and their [C/Fe] values to an expected value of −0.26 dex plus random error following a Gaussian distribution with = 0 dex and σ = 0.2 dex. We then calculated their new photometric magnitudes according to Section 2. Since normal dwarf stars (the remaining 99%) are typically not chemically enhanced, we assumed a solar chemical pattern and made no changes to their photometric magnitudes.

Figure 6 [Figure 6: see original paper] shows the u − g versus g − r color-color diagram for N-rich dwarf stars and normal dwarf stars in the metallicity bin [−1.2, −1.0]; diagrams for other metallicity ranges can be found in Figure A2 in the Appendix. Following a similar procedure as for giant stars, we obtained the border between the two populations (red curve) in Figure 6. However, this border was determined only for g − r = 0.28–1.40 mag (the same for all metallicity bins) because (1) the two populations show significant overlap at $g - r < 0.28$ mag, making separation difficult, and (2) the fit becomes significantly worse when extended to $g - r > 1.40$ mag, which corresponds to the less constrained "knee" feature in the lower main sequence. Table 2 shows the pollution rate, hit probability, and division line coefficients for different metallicity ranges.

According to Table 2, for all metallicity bins including the full range $[-1.8, -1.0]$, the hit probabilities are large and pollution rates are very small, suggesting that the $u - g$ versus $g - r$ color-color diagram can separate N-rich stars from normal stars with high efficiency. The hit probabilities for each metallicity bin exceed that for the full metallicity range, indicating that dividing the metallicity range can help select more N-rich dwarf stars.

3.3. Identification of N-rich Stars with Slitless Spectrograph

The slitless spectrograph (R 200) in the CSST main survey module covers several strong C, N, O-related molecular features and should therefore be suitable for separating N-rich stars from normal stars (see Section 2). To evaluate the required signal-to-noise ratio (SNR) for observations, we synthesized spectra with R 200 using ISPEC, then added Poisson noise to simulate CSST observed spectra with SNR of 20 and 10.

We selected a star with stellar parameters near the median values of the giant star sample as representative. Two spectra were generated following the chemical patterns of N-rich stars (green lines) and normal stars (blue lines) (upper panel of Figure 7 Figure 7: see original paper). To clearly visualize the molecular features, we calculated the flux ratio between these two spectra (lower panel of Figure 7(a)). To estimate their significance, we fitted Gaussian profiles (red lines) to the molecular bands in the flux ratio spectra, using the maximum depth of the Gaussian function to represent the "signal" of a molecular band (labeled "A"). The "noise" (σ) was calculated as the standard deviation of flux ratios from 450 to 500 nm. We defined the ratio of "signal" to "noise" as the significance level of each feature.

Three molecular features stand out clearly: NH3400, CN3839, and CN4142. At SNR = 20, the significance levels of NH3400, CN3839, and CN4142 are 39.1σ, 31.7σ, and 9.2σ, respectively (labeled in the bottom-left of the lower panel of Figure 7(a)). At SNR = 10, the significance levels are 27.0σ, 24.8σ, and 8.8σ, respectively. As SNR decreases, the significance levels of the molecular bands decrease, but all remain above 5σ at SNR = 10, suggesting that a spectrum with SNR = 10 is sufficient for separating N-rich giant stars from normal giant stars.

We performed the same analysis for a representative star from the dwarf star sample (Figure 8 [Figure 8: see original paper]). Compared to giant stars, only the NH3400 feature shows significant difference between N-rich and normal stars. The significance level of NH3400 is 53.6σ at SNR = 20 and 25.2σ at SNR = 10, both exceeding 5σ. This suggests that a spectrum with SNR = 10 is sufficient for separating N-rich dwarf stars from normal dwarf stars.

Given that N-rich stars can be identified in slitless spectra at a given SNR, the challenge remains of how to identify them among tens of millions of spectra. Multiple methods can accomplish this: (1) calculate spectral indices related to N features and select those with extreme values, as outlined in Tang et al. (2019, 2020); (2) apply outlier detection algorithms to slitless spectra with similar stellar parameters to identify N-rich stars with strong N-related features; among other approaches.

4. Discussion

Two practical issues affect photometric identification of N-rich stars. First, how accurately can we measure metallicity from CSST main survey photometry? Using artificial intelligence training, Haibo Yuan (private communication) suggests that retrieved metallicity accuracy is 0.1 dex for FGK solar-scaled abundance stars, which is smaller than the 0.2 dex metallicity bin width used in photometric identification. However, metallicity derivation strongly impacts u-band magnitudes, which are also affected by N abundances, raising concerns about degeneracy between metallicity and N abundance determination based on u-band magnitudes. This degeneracy can be broken using filters sensitive to either metallicity or N abundances. Theoretically, the NUV band should be more sensitive to metallicity than the u band due to numerous metal lines in the former. To verify this, we retrieved spectra from the PHOENIX synthetic library (Husser et al. 2013). Figure 9 [Figure 9: see original paper] shows flux differences in NUV and u-band filters for three red giant stars with different metallicities. The NUV-band magnitude is clearly sensitive to [Fe/H] but not to [N/H], as there are no strong N-related features in this band (see Figures 7 and 8). Therefore, the aforementioned degeneracy can be broken using NUV-band magnitude or related colors. However, relatively poor studies of oscillator strengths for absorption features in this band prevent further investigation, which is beyond the scope of this paper. Hopefully, upcoming CSST photometric and spectroscopic observations in the NUV band will provide calibration for theoretical spectra.

Since most metal-poor halo stars are alpha-enhanced, we further examined whether u-band photometry is strongly affected by $[\alpha/\mathrm{Fe}]$. Following the procedure above, we retrieved two spectra from the PHOENIX synthetic library with $[\alpha/\mathrm{Fe}] = 0.2$ and 0.4 at Teff = 4700 K, log g = 1.5, $[\mathrm{Fe/H}] = -1.0$. We found the magnitude difference in the u-band is negligible (0.005 mag). Therefore, alpha-enhancement does not affect [N/H] determination.

The second issue is the impact of photometric error. We added photometric errors in u, g, r bands for all stars in our catalog according to Qu et al. (2023). After including photometric errors, the efficiency of identifying N-rich stars drops significantly due to large photometric errors for fainter stars. To avoid large errors that blur boundaries, we limited our sample to brighter stars. We found that g = 18.5 mag achieves a good balance between maximizing sample size and minimizing pollution rate (Tables 3 and 4). These tables show reasonable hit probabilities and pollution rates, suggesting the method is valid for bright stars (g $<$ 18.5 mag). Figures 10 [Figure 10: see original paper] and 11 [Figure 11: see original paper] show the u $-$ g versus g $-$ r color-color diagrams for the metallicity bin [-1.2, -1.0] at g $<$ 18.5 mag. While 18.5 mag may seem bright for photometric surveys, it is in fact fainter than any currently identified N-rich field stars, which require spectroscopic observations.

5. Conclusion

GCs are among the oldest stellar systems in our MW, bearing witness to the Galaxy' s formation and evolution. During their co-evolution, GC stars can escape to the field, and retracing these stars is crucial for detailing the MW' s chemical evolution. The N-rich nature of chemically enhanced populations in GCs offers excellent prospects for identifying GC escapees using UV photometry and spectroscopy, such as with CSST.

Based on our mock photometric catalog of MW halo stars, we evaluated the efficiency of identifying N-rich stars separately for giants and dwarfs. We used ISPEC to generate spectra with various chemical patterns and added Poisson noise to mimic observed spectra with SNR of 10 and 20. We demonstrated that slitless spectra (R 200) with SNR = 10 are sufficient to identify N-related molecular features with significance greater than 5σ, enabling separation of N-rich stars from normal stars. In parallel, we generated spectra with different chemical patterns, convolved them with CSST main survey filters to simulate magnitude differences, and found that the u $-$ g versus g $-$ r color-color diagram can identify N-rich stars because the u band covers strong NH and CN molecular features.

Based on our mock catalog, we will identify a substantially larger number of N-rich stars than previously possible. This unprecedentedly large sample will provide a comprehensive dataset to test different MW formation scenarios and compare with N-body simulation results. For example, Gieles & Gnedin (2023) evaluated GC mass loss rates with stellar-mass black holes and found agreement between model and observed density profiles of N-rich (field) stars (see their Figure 12 [Figure 12: see original paper]), confirming their GC origin. In the near future, the largest sample of N-rich (field) stars identified using CSST photometry will reveal their spatial distribution, velocity distribution, and even chemical abundances at statistically significant levels. Combined with state-of-the-art N-body simulations, this will be promising for addressing many details of MW evolution.

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Appendix

Additional Figures

We display the $u - g$ versus $g - r$ color–color diagrams for the metallicity bins [−1.8, −1.0], [−1.4, −1.2], [−1.6, −1.4], and [−1.8, −1.6] below. Figure A1 shows results for giants and Figure A2 for dwarfs.

[The remainder of the Appendix and References sections follow exactly as in the original manuscript, with all figure references, tables, and citations preserved unchanged.]

Note: Figure translations are in progress. See original paper for figures.

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